Comparing Properties of Alternative Media for Stormwater Biofilters

A Thesis

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Dedication

This thesis is dedicated to my family who have shaped the person I am and motivate me every day.

Abstract

This study includes the classification and characterization of alternative biofiltration media. Materials were evaluated using a series of standardized tests. The performance and physical properties of alternative media were then compared to the currently specified biofiltration mixture of compost and sand.

Results from laboratory testing reveal that compost and peat have similar physical properties and infiltrate and retain water at similar rates. Muck soils were found to be inferior to compost by the same performance criteria. These results indicate that peat soils may be a viable alternative to compost for use as a soil additive for biofiltration devices.

This study also included the design of field test plots and the configuration of remote field monitoring equipment. The construction of six field test plots comparing compost and peat added as a soil amendment are described. Instrumentation was configured to collect long-term rainfall and water-storage data to evaluate performance in-situ.

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Chapter 1: Introduction

1.1 Introduction to Stormwater Biofilters

Stormwater biofiltration devices utilize a vegetated media to provide water quality treatment and water quantity control. The effectiveness of a stormwater biofiltration device is highly dependent on the properties of the media selected for its construction. The media used must support vegetative growth, provide water quality treatment and infiltrate a sufficient volume. Ability to provide these attributes is highly dependent on the infiltration rate and hydraulic conductivity of the media. Volume reduction increases with increasing conductivity as more water infiltrates to the subsurface. For water quality treatment, sufficient contact time between the stormwater, media, plant roots and any microbes that degrade stormwater pollutants necessitates a moderate conductivity. Finally, vegetative establishment and growth requires the retention of water sufficient for plant uptake. These needs make the determination of a biofiltration media's geotechnical and hydrologic characteristics important for the prediction of their stormwater treatment performance.

1.2 Study Need and Motivation

The Minnesota General Permit for Construction Stormwater issued under the National Pollutant Discharge Elimination System (NPDES) requires the retention of the first inch of runoff from newly constructed impervious surfaces (MPCA, 2013). Biofiltration devices are constructed specifically to meet the NPDES permit requirement. Current Minnesota Department of Transportation (MnDOT) specifications make use of known compost media and compost-sand media mixture characteristics to design stormwater management devices with predictable performance. Interest in alternative media options to meet NPDES permit requirements is increasing, but the characteristics and performance of alternative media such as peat, muck, and taconite tailings are largely unknown (Stenlund, 2014a). Peat is partially decomposed plant matter that is high in organic content and complex in chemical and physical structure (Kao and Lei, 2000). The term muck is commonly used to describe a wide variety of highly organic and highly decomposed soils (MnDOT, 2013) but is defined by the Michigan Department of Transportation (MDOT) Uniform Field Soil Classification System as amorphous peat. Amorphous peat is described as highly decomposed peat with little to no recognizable plant matter remaining. Taconite tailings are an iron-ore mining byproduct with a high iron content and physical properties that are similar with those of sand.

This research aims to characterize the hydrologic and geotechnical characteristics of peat, muck, and taconite tailings to determine how these media perform in comparison to compost and compost-sand mixtures. These media are available as construction and mining by-products in northern Minnesota. The beneficial reuse of these highly available byproducts make their characterization and performance evaluation important for efficiently and effectively managing stormwater in this region.

1.3 Scope

The scope of this research includes the collection, classification and laboratory characterization of peat, muck, taconite tailings, sand and compost for use in biofilters. In addition to laboratory tests required for classification, media was tested for compaction characteristics, hydraulic conductivity, water-holding capacity and strength. These parameters were deemed critical to biofilter performance in the field through a review of the literature.

From the laboratory test results, a comparison of alternative filter media to currently specified compost and sand mixtures was conducted. Geotechnical performance goals include meeting or exceeding the hydraulic conductivity and water-retention capacity of sand-compost mixtures. In addition to these goals, the media must provide water quality improvement and support vegetative growth. Project affiliates at the University of Minnesota Duluth Natural Resources Research Institute (NRRI) conducted concurrent research to determine the media's ability to satisfy these needs. Ultimately, a media meeting geotechnical, biological, and environmental treatment goals was selected for field study. Field pilot plots were then designed, constructed and instrumented for future long term monitoring of soil moisture, rainfall, runoff and temperature.

1.4 Organization of Paper

Chapter 2 contains a comprehensive literature review that provides the background necessary to understand the importance and need for this research. Chapter 3 describes media sample collection, laboratory testing methodology and field test design and construction. Chapter 4 presents results and analysis from laboratory testing. Chapter 5 presents conclusions, practical applications, concerns and future project extensions.

Chapter 2: Literature Review

2.1 Introduction

Chapter 2 provides context based on a review of available literature for the use of biofiltration Best Management Practices (BMP's) for the treatment of stormwater runoff. The performance and factors affecting the performance of biofiltration BMP's are reviewed. Additionally, a review and synthesis of research related to filter media and soil amendments for improving water absorption, physical properties, vegetative support and pollutant capture in biofiltration BMP's is provided. This review also examines the beneficial reuse of waste materials readily available in northern Minnesota.

The accumulation of pollutants on roadways can result in contaminated stormwater runoff that has a negative effect on receiving water quality, groundwater quality, and aquatic ecosystems (EPA, 1995). Pollutants accumulate on roadways via three primary mechanisms: atmospheric deposition, vehicle deposition, and maintenance activities (Barrett et al., 1995). Typically occurring roadway pollutants include suspended solids, heavy metals, excess nutrients (nitrogen and phosphorus), deicing chemical constituents, pesticides, herbicides, petroleum byproducts, organic compounds, and bacteria (Table 1). Median pollutant concentrations for highway runoff and discharge limits are also provided (Herrera, 2007).

Additionally, roadways increase impervious surface area resulting in an increase in runoff volume and peak discharge intensity. Increasing runoff volume and intensity can result in increased erosion and turbidity which has been linked to negative impacts on water quality and public health (Gaffield et al., 2003).

During dry periods, pollutants accumulate on roadways until a precipitation event occurs. The initial precipitation mobilizes the built-up pollutants and washes them off the road surface in what is known as "first flush" behavior (Kayhanian et al., 2012). First flush behavior implies that a large fraction of accumulated pollutants will be washed off in a relatively small fraction of initial stormwater runoff. The well documented occurrence of first flush behavior (Barrett, 1998; Bertrand-Krajewski, 1998; Deng, 2009; Gupta, 1996) has driven stormwater policy in the United States to focus on capturing and treating the first inch of runoff.

Table 1.Typically occurring roadway pollutants, their sources, nationwide median concentrations in stormwater and Minnesota discharge limits (Barber et al., 2006; Clar et al., 2004; EWGCC, 2000; Herrera, 2007; Kobriger, 1984; MPCA, 2015; TRB, 2006).

Pollutant	**Source**	**Median Concentration**	**Water Quality Standards***
Total Suspended Solids	Pavement wear, vehicles, atmospheric deposition, maintenance activities, snow/ice control	78.4 mg/L	10 mg/L
Heavy Metals	Atmospheric deposition, vehicle wear, highway structures, insecticides and fungicides, lubricants, diesel fuel, gasoline, asphalt paving	Cu: 11.1 µg/L Pb: 50.7 µg/L Zn: 129 µg/L	At hardness= 50 mg/L Cu: CS=6.4µg/L MS=9.2µg/L FAV=18µg/L Pb: CS=1.3µg/L MS=34µg/L FAV=68µg/L Zn: CS=59µg/L MS=65µg/L FAV=130µg/L
Nitrogen and Phosphorus	Atmospheric deposition, fertilizer applications, dead plant material, road-kill, sediments, exhaust	TN: 2 mg/L TKN: 1.47 mg/L NO_2+NO_3: 0.533 mg/L TP: 0.259 mg/L TSP: 0.103 mg/L	TP = 12-150 µg/L
Sodium and Chloride	Deicing salts	Cl- (MN): 116 mg/L	CS = 230 mg/L MS = 860 mg/L FAV = 1,720 mg/L

Table 1 (continued). Typically occurring roadway pollutants, their sources, nationwide median concentrations in stormwater and Minnesota discharge limits (Barber et al. (2006), Clar et al. (2004), EWGCC (2000), Herrera (2007), Kobriger (1984), MPCA (2015), TRB (2006).

Pollutant	**Source**	**Median Concentration**	**Water Quality Standards***
Polychlorinated biphenyl (PCB)	Atmospheric deposition	NA	CS = 0.014 ng/L MS = 1,000 ng/L FAV = 2,000 ng/L
Bacteria	Soil litter, wildlife waste, road-kill, trucks hauling livestock waste	570- 6,200 (Total coliform, CFU/100 mL)	NA

*Class 2 Aquatic Life and Recreation (Minnesota P.C.A. 2015).

NOTE: Cu=copper; Pb = lead; Zn = zinc; TN = total nitrogen; TKN = total Kjeldhal nitrogen; TP = total phosphorus; TSP = total soluble phosphorus; Cl = chloride; CS = chronic standard; MS = maximum standard; FAV = final acute value.

2.2 Policy and Regulations

In Minnesota, the construction of new impervious surfaces requires the builder to obtain a Construction Stormwater General Permit issued in accordance with the NPDES permit. The NPDES Construction Stormwater permit is issued in compliance with the Clean Water Act of 1972 including more recent amendments which address stormwater directly (MPCA, 2013). The permit explicitly requires the retention and treatment of the first inch of runoff from new construction. Linear construction projects, such as roadways, present unique issues for achieving compliance due to the variety of land types encountered and limited “right-of-way” acquisition. Solutions to these issues include biofiltration systems such as bioslopes and bioswales (Stenlund, 2014a).

2.3 Best Management Practices: Bioslopes and Bioswales

A bioswale is a vegetated channel designed to provide linear conveyance, retention, and water quality treatment of stormwater (Figure 1). A bioslope (Figure 2) is a flat vegetated slope designed to provide sheet flow conveyance, retention and treatment of runoff. Bioslopes and bioswales are often constructed as a treatment train with the bioslope conveying sheet flow to the bioswale for linear transport (Figure 3). Both improve receiving water quality by volume and pollutant concentration reduction (Barrett et al, 1998). Mechanisms for water treatment include volume reduction through infiltration into the soil, physical filtration by soil media, sedimentation, biological treatment by plant uptake and microbial action, and adsorption through interaction with soil particles (Barrett et al, 1998). A comparison by Claytor and Schueler (1996) of several BMP types found that bioswales and bioslopes provide moderate to high levels of removal for heavy metals, total suspended solids, and nutrients. The primary advantage of bioslopes and bioswales is the relatively low cost (Deletic, 2005) and feasibility of construction (Stenlund, 2014a).

Figure 1. A bioswale adjacent to a highway (California Department of Transportation (Caltrans), 2015).

Figure 2. Bioslope adjacent to a highway (Caltrans, 2004).

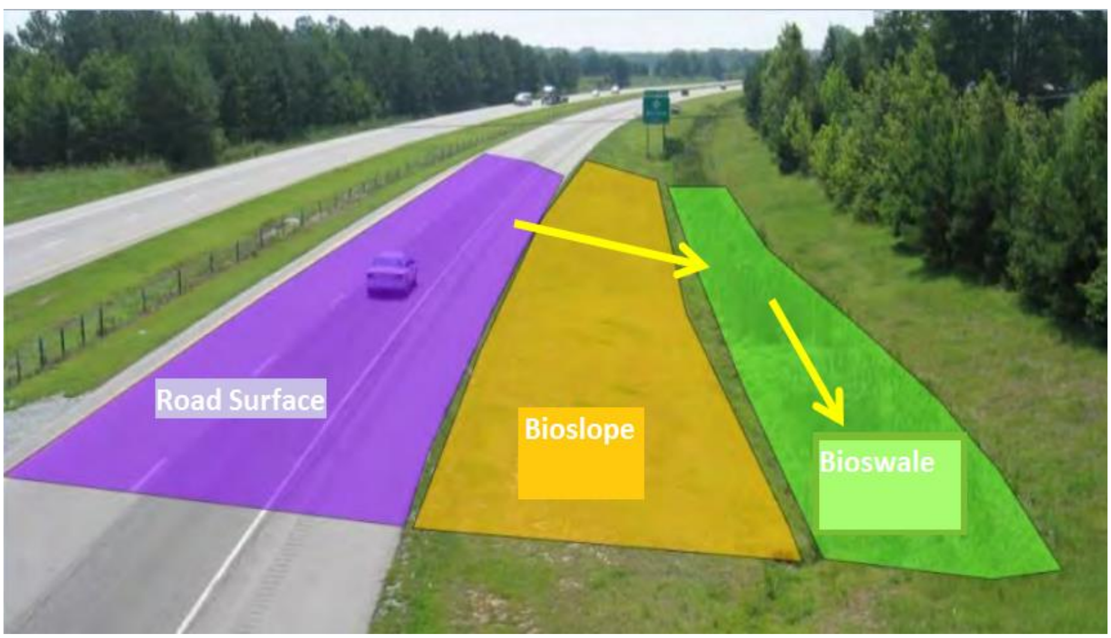

Figure 3. A highway bioslope and bioswale treatment train (Adapted from North Carolina Department of Transportation, 2012).

2.4 Performance of Bioslopes and Bioswales

A review of the literature on the performance of bioslopes and bioswales for removal of pollutants reveals that, relative to cost, these BMP's provide high levels of treatment. Commonly studied pollutants and removal efficiencies are summarized in Table 2. High removal rates of suspended solids and moderate removal rates of metals indicate that bioslopes and bioswales can be used to effectively treat stormwater. Several design factors control the effectiveness of bioslopes and bioswales. Due to their effect on bioslope and bioswale performance, the optimization of these factors could provide enhanced stormwater pollutant treatment abilities.

Table 2. Pollutant removal efficiencies from field studies of bioslopes and bioswales.

Reference	BMP Type	Removal Efficiency			
		Suspended Solids	**Heavy Metals**	**Nutrients**	**BOD & COD**
Backstrom, 2002	Bioswale	79-98%			
Barrett, 2008	Bioswale	60%	Total: Zn= 62% Dissolved: Zn= 24%	Total: 60% Dissolved: 40%	**
Barrett, 2004	Bioswale	86%	Pb= 30%, Zn=87%	N=35%, TKN=39% P=38%	
Barrett et al., 1998	Bioswale	85-87%	Zn=75% Pb=17% Fe=75%	Total P=34-44%, TKN=23-50%	COD= 61-63 %
Barrett, 2004	Bioslope	72%	Total: Cu=80% Pb=87%, Zn=80%;		

Table 2. Pollutant removal efficiencies from field studies of bioslopes and bioswales.

Reference	**BMP Type**	**Removal Efficiency**			
		Suspended Solids	**Heavy Metals**	**Nutrients**	**BOD & COD**
			Dissolved:Cu=68%, Pb=7%, Zn=72%		
Biesboer and Elfering, 2003	Bioswale	50%, 70%*		TP=22%, ortho-P=42% 54%*,52%*	
Davis and Stagge, 2005	Bioswale	79%	Cu=46%, Pb=35%, Zn=50%	TKN=-2%, Nitrate=46% Nitrite=84%, Total P=-72%, Cl=-295%	
Deletic et al., 2009	Bioslope	35-90%		Ortho-P=5-50%, Solid N= 35-90%, 14% for soluble N	
Yousef et al., 1987	Bioswale		35-93% depending on metal		
Yu and Kaighn, 1995	Bioslope	63.9%	Zn= 87.6%	-21.2 TP	59.3% COD

BOD= Biological Oxygen Demand, COD= Chemical Oxygen Demand
**= COD removal observed when influent concentration exceeds 80 mg/L, *= after check dam installation

2.4.1 Design Performance Factors for Bioslopes and Bioswales

Several design factors that control the effectiveness of biofiltration devices have been identified from a review of the literature. These factors include the characteristics of the filtration media used, the characteristics of the vegetation and the geometry or physical dimensions of the constructed bioslopes and bioswales (Barrett et al., 1998). Infiltration rate, initial moisture content and compaction of filter media have also emerged as critical factors effecting performance (Ahmed et al., 2015; Gulliver et al., 2014; Hatt et al., 2008). Of these factors, filter media appears to have the most potential for innovation and improved performance due to the variation in available media.

2.4.2 Volume Reduction and Infiltration Capacity

The rate of infiltration in biofilters controls stormwater runoff volume reduction, exposure of pollutants to potential sorbents, the ability of the soil media to act as a physical filter, and the recharge of groundwater (Claytor and Schueler, 1996; Larson et al., 2008; Emerson et al., 2008). Field infiltration rates have been found to be highly variable resulting in varying volume reduction capabilities in biofilters (Yousef et al., 1987, Ahmed et al, 2015). Gulliver et al. (2014) provides a summary of swale volume reduction capabilities from several studies with a range of 9-100 percent reduction.

Despite this variability, volume reduction is a consistent and reliable way to reduce pollutant mass loads to surface waters even when overall pollutant concentration is unaffected (Pitt and McLean, 1986). Yousef et al. (1985) also found strong correlation between volume reduction and the nutrient removal capabilities of six swales as presented in Figure 4.

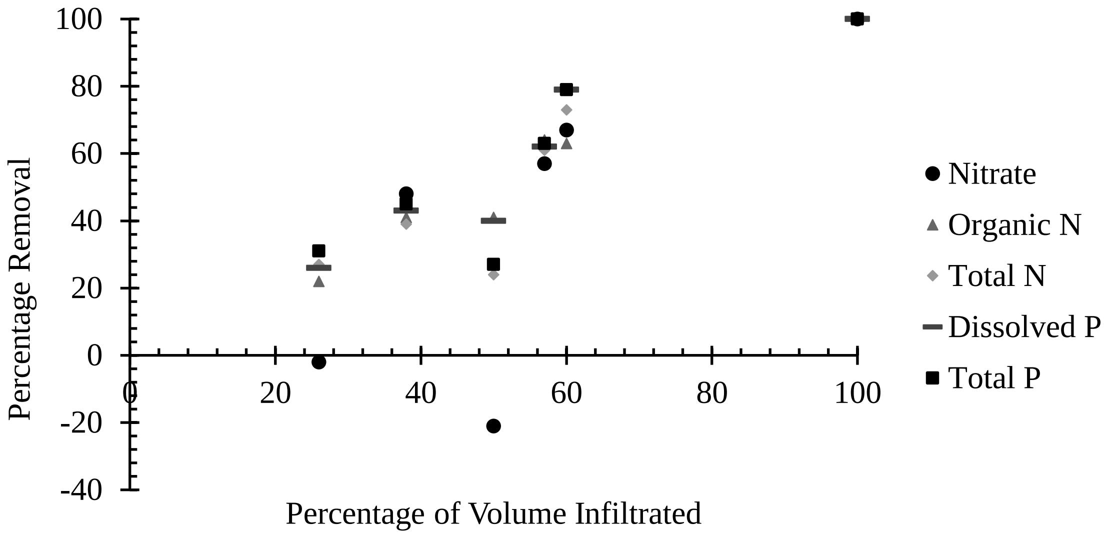

Figure 4. Percentage of pollutant removed versus volume infiltrated in bioswales (Yousef et al., 1985).

The strong correlation between pollutant removal capability and volume reduction by infiltration has led several researchers to recommend infiltration rate as a key parameter when designing biofilters (Abida and Sabourin, 2006; Backstrom, 2003; Claytor and Schueler, 1996). Additionally, Barr Engineering Company performed a simulation of swale design parameters using the Minnesota Pollution Control Agency (MPCA) designed MIDS calculator to assess the effect on annual volume reduction. Of the five parameters tested, infiltration rate exhibited the highest degree of control on annual volume reduction percentage. Channel length also exhibits substantial control; however, for linear construction projects, channel length is a function of newly added impervious surface length. Accordingly, the loading rate will increase in proportion to channel length making channel length less relevant. Side slope was found to have a weak effect on annual volume reduction percentage. Design side slope will likely be limited by slope stability considerations rather than infiltration optimization. The effect of Manning's roughness values on infiltration in this model agrees with research by Backstrom (2003) which found that vegetation density is positively associated with total suspended solids (TSS) removal efficiency. A summary of recommended design infiltration rates is presented in Figure 3. In most cases, a minimum design infiltration rate of 0.5 in/hr is recommended in biofiltration systems where freezing and clogging are not likely.

Table 3. Recommended infiltration rates for stormwater BMP's in various locations.

Reference	**Recommended Minimum Infiltration (in/hr)**	**Notes**
Claytor and Schuler, 1996	0.25 in/hr	Conservative to account for clogging
EPA, 1999	0.5 in/hr	Vegetated swale
PAEPA, 2006	0.5 in/hr	Vegetated swale
Iowa Stormwater Management Manual, 2009	0.3 in/hr	Swales
NRCS, 2005	0.5 in/hr	Bioswales
Stenlund, 2014b	1.02 in/hr	Unless underdrain is provided
MnDOT Construction Specs, 2014	4.0 in/hr minimum	Filter media

While the infiltration rates presented in Table 3 are a recommended minimum, Yousef et al. (1985) suggests that higher rates are preferable. It is also recommended to use a factor of safety of 2 to 3 with infiltration rates to account for the negative impacts of freezing, clogging, and compaction (Abida and Sabourin, 2006). In Minnesota, where freezing is common and salting and sanding of roadways increases sediment loads and potential for clogging, a minimum infiltration rate of 4 in/hr is required for filtration media topsoil (MnDOT, 2014). The Minnesota Construction Stormwater Permit designates a maximum infiltration rate of 8.3 inches/ hour to ensure water retention suitable for plant growth and contact time for pollutant removal. The Minnesota Stormwater Manual recommends infiltration rates for biofiltration devices, including bioslopes and bioswales, be between 1in/hr to 8 in/hr. These design guidelines reflect the consideration of cold weather climates. The impact of cold climates on infiltration is a function of the time and rate of draining between wetting and freezing. Longer drainage times in poorly draining soils, such as clays, result in frozen infiltration capacities of 5% of those observed in thawed conditions. Soils that are free draining retain a frozen infiltration capacity equal to 30% of thawed conditions (Al-Houri et al., 2009). Compaction has also been found to reduce infiltration capacity by 70-99% (Gregory et al., 2006). The detrimental effects of clogging and compaction are partially mitigated by plant root action as explained further in the following section (Deletic et al., 2009).

2.4.3 Vegetation

Vegetation has several important roles in the performance of stormwater biofilters. First, by slowing the runoff velocity as it is conveyed across a biofilter, vegetation increases settling of suspended solids and infiltration rate (Backstrom, 2003; Gulliver, 2014). Backstrom (2002) found that the highest suspended solids removal rates occurred in swales with the densest vegetation. Additionally, Barrett (2004) found that solids removal performance of buffer strips declined rapidly when vegetation coverage fell below 75-80%. Second, vegetation can alleviate the effects of clogging and compaction thereby maintaining higher infiltration rates (Read et al., 2008). This alleviation is due to plant root action and can maintain or improve infiltration rates of the soil, a previously discussed and important factor to performance (Deletic, 2009). Finally, plants and the microbes supported by plant root zones uptake heavy metals and nutrients from stormwater that would otherwise discharge to receiving waters, possibly inducing toxicity and eutrophication (Read et al., 2008; Pham, 2012).

Native plants are the preferred vegetation for Minnesota roadsides due to their reduced maintenance needs (mowing and reseeding), increased ability to provide roadside habitat and diversity, and their ability to reduce exotic and invasive weed infestations (Benik, 1998). Native plants are also recommended for stormwater treatment systems because of their hardiness and the wide range of ecosystem functions they provide (Shaw and Schmidt, 2003). A stormwater site seed mix (Stormwater Northeast 33-361) consisting primarily of native species adapted to northeast Minnesota is specified by MnDOT (2014).

There are limitations to plant establishment and growth in bioswales. Persistent inundation of bioswales significantly inhibits plant germination. Shading by trees or shrubs also negatively impacts plant growth (Mazer et al., 2001). Other environmental factors that can influence plant growth in bioswales include limited water, sediment loads, pollutants and toxins, nutrients, deicing salts, erosion, turbidity, invasive species and herbivores (Shaw and Schmidt, 2003).

While plant species vary in their abilities to treat stormwater due to their wide variety of physical and physiological characteristics (Read et al., 2008), in general the addition of vegetation reduces stormwater pollutant concentrations and loading rates. Comparing the effect of vegetation and soil media on the removal of nitrogen, phosphorus, and carbon, Henderson et al. (2007) found that vegetated biofilters outperformed non-vegetated biofilters in all soil types. The improvements in pollutant reduction (Table 4) were attributed to the uptake by plants and microbes living in the root zone. Henderson et al. (2007) also note that microbial and plant uptake results in a long-term stabilization of nutrients with reduced risk of leaching during subsequent rainfall events. In addition to the water quality benefits, vegetation also plays an important role in slope stability.

Table 4. Experimental increases in pollutant removal with the establishment of vegetation on biofilters (adapted from Henderson et al., 2007).

	Percent Increase in Reduction with Addition of Vegetation		
Nutrient	**Gravel**	**Sand**	**Sandy-loam**
PO_4	50	0	23
NOx	219	347	384
NH_4	6	24	-1
TP	54	4	16
TN	75	67	52

2.5 Soil Amendments and Filtration Media

An effective biofiltration soil media must be able to infiltrate stormwater at a high rate, support vegetative growth, provide water quality improvement, and maintain its structural integrity to prevent erosion and slope failure (Stenlund, 2014c). Where *in-situ* soils do not perform these functions well, soil amendments are implemented (Washington Department of Transportation (WSDOT), 2014). Currently recommended soil amendments for filtration media used in bioslopes and bioswales is composed of 60-80% clean sand and 20-40% organic compost by volume (MnDOT, 2014). These recommendations are based on experience showing that the mixture will result in compliance with the NPDES requirement to retain the first inch of stormwater runoff. The ability of salvage materials such as peat, muck, and taconite tailings, which are locally available in northern Minnesota, to meet this requirement is unknown. Study and characterization of these materials will reveal their ability to perform these functions as compared to the currently recommended sand and compost mix. In addition, the beneficial reuse of these materials as filtration media in bioslopes and bioswales has the potential to reduce project cost, increase stormwater treatment performance, and reduce waste material.

2.5.1 Compost

Compost has been established as the organic material of choice for biofiltration soil amendments due to its ability to adsorb heavy metals, improve infiltration of stormwater, support plant growth, and reduce erosion (Seelsean, 2006; Maurer, 2009; Pitt et al., 1999). Compost is either blended in a filter media bed or applied as a surface-layer blanket (WisDOT, 2014). Numerous studies have investigated the stormwater treatment capabilities of compost. In one study, green waste compost, derived from grass clippings, brush trimmings, and plant materials was found to have superior metal absorption capabilities when compared to several other soil amendments including peat, coir, bonemeal, and woodbark (Nwachukwu and Pulford, 2008). Compost's high adsorption capacity is attributed to its relatively high cation exchange capacity and neutral pH (Khan et al., 2009; Claytor and Schuler, 1996). Seelsaen et al.'s (2006) laboratory batch studies demonstrated excellent removal efficiencies of copper, zinc and lead for stormwater treated with a compost filter (Table 5). A three-year field-monitoring study of a compost filter system, summarized in Table 5, also found high removal efficiencies for several stormwater pollutants (CSF Treatment Systems Inc., 1994).

Nwachukwu and Pulford (2008) noted that these removal efficiencies are negatively affected in the presence of high salt concentrations and other metal ions due to competitive sorption. Seelsaen et al. (2006b) reported that compost with smaller particle size had a larger surface area and thus greater sorption potential; however, Faucette et al. (2007) warn that if particle size distribution specifications are not met, total soil loss, suspended solids, and turbidity was increased. These findings suggest that there is an optimal particle size distribution for stormwater treatment purposes that balances adsorption potential and erosion control.

Table 5. Removal efficiencies of compost filters in lab and field experiments (adapted from Claytor and Schueler, 1996).

Pollutant	**Setting**	**Removal Efficiency**
Total Suspended Solids	Field	95%
Total Dissolved Solids	Field	(-37%)
COD	Field	67%
Total Phosphorus	Field	41%
Soluble Phosphorus	Field	(negative)
Organic Nitrogen	Field	56%

Table 5. Removal efficiencies of compost filters in lab and field experiments (adapted from Claytor and Schueler, 1996).

Pollutant	**Setting**	**Removal Efficiency**
Nitrate	Field	(-34%)
Cadmium	Field	No Data
Lead	Lab	97%
Zinc	Field, Lab	88%, 88%
Copper	Lab	93%
Hydrocarbons	Field	87%
Copper	Field	67%

Infiltration capacity and volume reduction enhancements by compost amendments are reported throughout the literature. Faucette et al. (2005) compared compost blankets to a “hydroseed” and silt fence system and found that compost blankets reduced runoff volumes by five times that of the hydroseed treatment after three months and by 24% after a full year. Faucette et al. (2007) found that increasing percentages of compost in an erosion control blanket resulted in improved volume reduction and reduced runoff rates. A laboratory comparison of fourteen different erosion control practices showed that compost outperformed all other systems with volume reductions between 29% and 94%

for varying rainfall intensities (Faucette et al., 2009). Glanville et al. (2004) also reported significantly enhanced infiltration capacity on compost amended bioslopes. The ability of compost to improve infiltration enhances the overall performance of biofilters by providing volume reduction and increased contact with adsorptive media.

Yard waste compost soil amendments also improve vegetative cover and reduce erosion. Faucette et al. (2006) reported that yard waste compost blankets produced 2.75 times the vegetative cover of hydroseed treatments while also controlling weed growth. Pitt et al. (1999) also found improved vegetative cover on compost amended soils. Additionally, compost supports a healthy microbe population which improves nutrient availability to plants and reduces soil erosion (Archuleta and Faucette, 2014; Rushton, 2001). Faucette et al. (2009) found that compost blankets reduced soil erosion by 67-99% when compared to 14 other erosion control methods.

The performance of compost amended soils is heavily dependent on the quality of compost utilized (Archuleta and Faucette, 2014). Soil pH, moisture content, organic matter percentage, particle size, biological stability, and initial pollutant concentrations should all be considered when using compost for stormwater treatment. Specified properties for MnDOT Grade 2 compost used as a soil amendment to improve pollutant removal, enhance plant growth, reduce erosion, and provide volume reduction are presented in Table 6.

A potential issue associated with compost amended soils is nutrient leaching. Evidence for nutrient leaching is mixed. Some studies report removal of nitrogen and phosphorus (Faucette et al., 2005; Glanville et al., 2004), while others note that leaching of nitrogen and phosphorus is possible (Gulliver et al., 2014; Lenth and Dugapolski, 2011; Faucette et al., 2007; CFS Inc., 1994). Excess nutrients have the potential to cause eutrophication in receiving waters leading to suggestions by Faucette et al. (2005) that federal specifications for nutrient contents of soils used in stormwater management be developed. MnDOT (2014) notes that adequately matured grass or plant feedstock compost has less potential to leach nutrients than that made from biosolids or animal manure. Gulliver et al. (2014) suggest that phosphorus removal can be enhanced through the addition of iron based soil amendments while others have found peat to be effective for nutrient removal. Both topics were explored in the following sections on peat and taconite tailings.

Table 6. MnDOT Grade 2 Compost Requirements (MnDOT, 2014).

Requirement	**Range**
Organic matter content	≥ 30%
C/N ratio	6:1-20:1
pH	5.5-8.5
Moisture content	35%-55%
Bulk Density	700 lb per cubic yard- 1,600 lb per cubic yard
Inert material*	≥ 3% at 0.15 in (4mm)

Table 6. MnDOT Grade 2 Compost Requirements (MnDOT, 2014).

Requirement	Range
Soluble salts	≤10 mmho per cm
Germination test**	80%-100%
Screened particle size	≤3/4 (19mm)
*Includes plastic bag shreds, **must list species used	

Immature compost can be detrimental to plant growth. Maturity tests have been developed for evaluating compost to ensure its benefit to plants (University of Florida, 2011). Toxic contaminants such as pesticides can also be found in compost. Toxicity tests have been developed to determine their presence and effect on plant growth (ASTM, 2014; US Composting Council, 2015). These tests generally consist of plant bioassays, using seeds of fast growing plants such as lettuce or radish grown on the substrates being evaluated. Plant growth characteristics such as seed germination, root elongation, and seedling vigor are compared to a control to determine the safety of the tested substrates.

2.5.2 Peat and Muck

Peat is partially decomposed plant matter that is high in organic content and complex in chemical and physical structure. Peat is generally acidic in nature due to the presence of various functional groups in lignin that include alcohols, aldehydes, ketones, acids (such as humic acid and fulvic acid), phenolic hydroxides, and ethers (EPA, 1999; Gupta et al., 2009). The use of peat for stormwater treatment is appealing due to its low cost, local availability, high water-holding capacity, infiltration capabilities, good vegetative support capabilities, ability to improve soil properties and to filter and adsorb pollutants (Biesboer and Elfering, 2004). Farnham and Brown (1972) found significant reductions of phosphorus and organic pollutants in municipal wastewater treated with a peat and sand filter. Galli (1990) reports high removal efficiencies for typical stormwater pollutants treated with a peat-sand filter as shown in Table 7.

Table 7. Pollutant removal efficiencies of peat-sand filters (Galli, 1990).

Pollutant	**Removal Efficiency (%)**
Suspended Solids	90
Total Phosphorus	70
Total Nitrogen	50
BOD	90
Trace Metals	80
Bacteria	90

Numerous other studies have found peat to be effective for pollutant removal, primarily in heavy metal uptake, as shown in Table 8 (Brown et al., 2000; Gundogan et al., 2004; Ringqvist et al., 2002; Kao and Lei, 2000). Several authors note that peat's ability to capture heavy metals is dependent on pH with an optimal range of 3.5-8.5 (Pitt et al., 1997; Brown et al., 2000; Sharma and Foster, 1993, Crist et al., 1996). In general, peat can remove 50% of heavy metals at high concentrations and more than 90% at low concentrations (Sharma and Forster, 1993; Crist et al., 1996; Gundogan et al., 2004; Al-Faqih et al., 2008; Gupta et al., 2009; Izquierdo et al., 2009). The high metal removal capability of peat is attributed to its high cation exchange capacity, buffering capacity, and high adsorptive surface area (Biesboer and Elfering, 2004). Metals are taken-up by peat through ion exchange, complexation, surface adsorption and chemisorption (Crist et al., 1996; Brown et al., 2000; Gundogan et al., 2004).

Table 8. Summary of peat application on removal of metals, nutrients and organic matter in stormwater runoff.

Chemicals	**Lab/field**	**Pollutant removal efficiencies**	**Filter material**	**Inflow**	**Reference**
Cu, Ni	Lab	Maximum adsorption capacity 17.6mg/g and 14.5 mg/L for Cu and Ni respectively	Peat moss	Lab synthesized water	Gupta et al., 2009
Organic chemicals	Pilot plant	50-80% for BPA, 63% for PAHs	Peat moss	Landfill leachate	Kalmykova et al., 2014
Cu	Lab	22, 36.4, 43.7 mg/L for pH values of 4, 5 and 6 respectively	Mineralized peat	Lab synthesized water	Izquierdo et al., 2009
Cd, Cu, Ni, Zn	Lab	Zn = 28%, Cd=27%, Ni=24%, Cu=21%	Peat-based sorbent	Lab synthesized water	Al-Faqih et al., 2008

Table 8. Summary of peat application on removal of metals, nutrients and organic matter in stormwater runoff.

Chemicals	**Lab/field**	**Pollutant removal efficiencies**	**Filter material**	**Inflow**	**Reference**
Mg, Mn, Ca, Ni, Zn, Cd, Cu, Pb	Lab	At high concentration, uptake around 50% of Cd and Zn; at low concentration, remove 90% of Cd and Zn	Peat moss	Lab synthesized water	Crist et al., 1996
Cu	Lab	Remove over 90% of Cu	Herbaceous peat		Gündoğan et al., 2004
Cr	Lab	Highly dependent on pH, up to 100% removal at pH below 2.0	Peat moss	Lab synthesized water	Sharma and Forster,1993
N, P, BOD	Field & lab	Efficient removal of P and BOD, 50% removal efficiency in winter.	Peat moss, reed-sedge	Wastewater from municipal sewage plant	Farnham and Brown, 1972

Nitrogen and phosphorus are the primary nutrients in stormwater runoff, originating from atmospheric deposition, roadside fertilizer application and transported solids (Haering et al., 2006). Dissolved nitrogen is generally present in the forms of NO_3^-, NO_2^-, NH_4^+, NH_3 and organic nitrogen. The high solubility of nitrogen chemicals results in low adsorption rates in peat. However, a vegetated filtration system may improve nitrogen removal by plant uptake.

Peat has been found to be efficient in removing highly concentrated phosphorus, such as what is typically present in wastewater and agricultural runoff. The removal efficiency could be as high as 99% at low inflow rates and under aerobic conditions. Phosphorus concentrations in effluent water could be as low as 0.01 mg/L under these circumstances (Farnham and Brown, 1972). Peat filtering systems remove phosphorus through a combination of microbial assimilation, inorganic and organic retention and adsorption processes (Farnham and Brown, 1972). High carbon to phosphorus ratio (approximately 500-700:1) can provide sufficient carbon sources for microbial organisms to convert inorganic phosphorus into organic phosphate complexes. Vegetation can further improve the immobilization of phosphorus by plant uptake. However, stormwater usually has low concentrations of phosphorus, generally ranging from 0.1 to 0.4 mg/L (Kayhanian et al., 2012). A mixture of peat with other iron or aluminum rich materials may improve the removal efficiency since phosphorus can be adsorbed on aluminum and ferric hydroxides (LeFevre et al., 2014).

The hydraulic properties of peat are highly variably depending on the degree of decomposition and origin (Grover and Baldock, 2013). Nichols and Boelter (1982) reported hydraulic conductivities ranging from 7.0×10^{-5} cm/sec to 4.0×10^{-2} cm/sec. In general, greater decomposition correlates to lower hydraulic conductivity (Pitt et al., 1997). Since peat continues to decompose after harvest and application, changing conductivity presents a potential issue for long term performance of peat amended biofiltration devices (Stenlund, 2014b). Therefore, more frequent maintenance or replacement of filtration materials may be required. It is also important to note that peats of different botanical origin decompose at different rates. Sphagnum peat decomposes three times faster than sedge peat when exposed to oxygen (Raviv & Inbar, 1986). Plant derivation, moisture content, and compaction also affect peat's hydraulic conductivity (Clark and Pitt, 1999). The impact of these factors means that peat's physical and chemical structure, compaction, and decomposition status are important to its performance as a stormwater filtration media.

Plant establishment and growth is important for nutrient uptake and erosion control (Nichols and Boelter, 1982; Johnson, 2000). Peat helps retain soil moisture, reduce bulk density and improve microbial health, aiding in plant growth (Biesboer and Elfering, 2004; Pitt et al., 1997). Sloan et al. (2008) demonstrated that adding peat to sand significantly improved vegetative growth in a laboratory environment.

The pollutant removal capabilities, water absorbing capacity and soil improving properties of peat make it a useful soil amendment for biofiltration. In northern Minnesota, peat is often discarded during road construction making it readily available and affordable. These factors make it a viable alternative to compost for stormwater treatment applications.

Muck is differentiated from peat primarily by its degree of decomposition. Muck is a highly decomposed organic soil that is often excavated from construction sites due to its lack of structural integrity and low hydraulic conductivity (MnDOT, 2013). Since muck has limited use as a construction material, it is readily available at low cost. Research on muck for use as a soil amendment in stormwater treatment filtration media is limited, but due to its expected organic matter content it may aid in the establishment of vegetation in sandy, inorganic soils. Sileshi (2013) also notes that organic materials often have high cation exchange capacities and will improve the adsorption potential of a filter media.

2.5.3 Taconite tailings

The use of taconite tailings as an alternative stormwater filtration media offers several potential advantages including availability, favorable geotechnical properties, and possibly enhanced phosphorus removal. Taconite tailings are readily available in northern Minnesota as an iron ore mining byproduct. It is estimated that the production of one ton of taconite pellets generates nearly an equal amount of course tailings, largely considered waste product (Zanko et al., 2003). The beneficial reuse of these tailings for stormwater filter media may offer a mutually beneficial solution to stormwater managers and the mining industry.

The advantageous physical properties of taconite tailings include high strength and high hydraulic conductivity (Lund, 2014; Zanko et al., 2003). These properties will improve the stability and infiltration capacities of soils used in bioslopes and bioswales. In addition to the favorable physical properties, the iron content of taconite tailings may improve the ability of stormwater filters to remove phosphorus. Erickson et al. (2007, 2010, 2012) demonstrated a significant increase in the removal of dissolved phosphorus from stormwater when filters are amended with iron filings. Field application studies of iron enhanced-sand filtration trenches showed an 85-90% reduction in phosphorus loads to stormwater ponds (Erickson et al., 2012). Moreover, heavy metals may bind to hydroxide iron and precipitate onto sorbent surfaces, theoretically improving the removal of heavy metals from stormwater (Smith and Falls, 2001; Wu and Zhou, 2009).

Though taconite tailings are not typically conducive to plant growth due to low nutrient content and low moisture retention capability, amendments with organic materials have shown that substantial vegetative growth is possible (Norland and Veith, 1995). Felleson (1999) found that as little as 10 to 22.4 metric tons/ha of organic material applied to bare, coarse taconite tailings was sufficient for establishing vegetative cover. Potential issues associated with taconite tailings include increased transportation costs due to high bulk density (Zanko et al., 2007).

2.6 Optimizing Physical Properties of Filtration Media Soils

Effective bioslopes and bioswales must improve water quality, support plant growth and maintain the physical properties necessary to prevent erosion. In many ways, the ability of bioslopes and bioswales to meet performance requirements are dependent on the physical properties of the soil employed as a filtration media. Important parameters include hydraulic conductivity, water-holding capacity, response to compaction and strength (Sileshi, 2013).

The hydraulic conductivity and response to compaction can be optimized in a filtration media by maximizing the content of sand or other coarse grained inorganic material such as taconite tailings. Sileshi (2013) found that the negative impact on infiltration associated with compaction of soils was mitigated by increasing sand content in biofilter media mixtures. The infiltration capacity of soils with high organic content, particularly peat, was negatively affected by compaction. These findings suggest that hydraulic performance can be optimized by maximizing the amount of sand or taconite tailings in a media mixture, however, to meet environmental and biological project goals, a certain amount of organic material must be included.

Soil strength is important for slope stability. Strength can be optimized by maximizing permeability, particle angularity, particle size, and compaction while minimizing organic content (Coduto et al., 2013). While slope stability should be considered in the design and construction of bioslopes and bioswales, their effectiveness for stormwater treatment is negatively affected by soil compaction (Sileshi, 2013). In addition, a lack of organic content reduces vegetative support and promotes erosion (Fauccette et al., 2007). Ultimately, a useful biofiltration media mix design must balance infiltration rate and strength requirements with growth support, water quality improvement and erosion control requirements. This means that mixtures following MnDOT guidelines of 20-40% organic materials should be employed.

2.7 Conclusion

Bioslopes and bioswales are effective stormwater management devices suitable for meeting NPDES requirements requiring the capture of the first inch of runoff from highway construction projects. The efficiency of bioslopes and bioswales to capture runoff and improve water quality is highly dependent on the media from which they are constructed. Media characteristics of importance include infiltration capacity, resistance to compaction, ability to support vegetation, pollutant adsorption capacity, pH, and chemical composition. These parameters can be optimized in alternative filter media, through proper media selection, to satisfy biological, environmental, hydrological, and geotechnical performance goals.

Chapter 3: Methodology

3.0 Introduction

Chapter 3 provides a description of tests and procedures used to classify and characterize filter media for stormwater biofiltration devices. Materials studied include commercial compost, peat, muck, sand, taconite tailings and native soils from a field test site. Laboratory testing focused on classification, hydraulic conductivity, water-holding capacity and compaction characteristics. There were three main objectives of the tests: (1) to classify the study materials for aiding in the reproducibility of the study results; (2) to define the properties of the individual study media to predict their performance *in-situ*; and (3) to inform the development of filter media mixtures that optimize the stormwater treatment performance in biofiltration devices. Additionally, the design and construction of field test plots are described. The performance of several new filter media mixtures was compared to existing compost based media mixtures as defined by MnDOT (2016) and outlined in the following section.

3.1 Current Filter Media Specifications

MnDOT (2016) calls for a filter media topsoil mixture of 60%-80% sand meeting particle size requirements shown in Table 9 and 20%-40% Grade 2 compost as defined in Table 2. This sand-compost mixture is designed to support plant growth, provide water quality enhancement and infiltration at a rate of 4 in/hr. New filter media mixtures were designed and assessed using this specification. In addition to the requirements in Table 2, Grade 2 compost must also be “humus-rich, derived from the decomposition of leaves and yard wastes and have a texture that is similar with shredded peat” (MnDOT, 2016).

Table 9. Particle size distribution requirements for fine aggregate (MnDOT, 2016).

Sieve Size	Percent Passing by Weight (%)
⅜ in [9.50 mm]	100
No. 4 [4.75 mm]	95 – 100
No. 8 [2.36 mm]	80 – 100
No. 16 [1.18 mm]	55 – 85
No. 30 [600 µm]	30 – 60
No. 50 [300 µm]	5 – 30
No. 100 [150 µm]	0 – 10
No. 200 [75 µm]	0 – 2.5

Table 10. Summary of Grade 2 compost requirements (MnDOT, 2016)

Requirement	Range
Organic matter content	≥ 30 %
Carbon/Nitrogen ratio	6:1 – 20:1
pH	5.5 – 8.5
Moisture content	35% – 55%
Bulk density	700 lb per cu. yd – 1600 lb per cu. yd [415 kg per cu. m – 890 kg per cu. M]
Inert material*	< 3% at 0.15 in [4 mm]

Table 10. Summary of Grade 2 compost requirements (MnDOT, 2016)

Requirement	**Range**
Soluble salts	≤ 10 mmho per cm
Germination test**	80% – 100%
Screened particle size	≤ ¾ in [19 mm]
* Includes plastic bag shreds. ** Germination test must list the species of Cress or lettuce seed used.	

3.2 Individual Treatment Media Characterization

Individual treatment media was characterized to inform filter media mix design and provide a comparative analysis to currently specified filter media, i.e. sand and compost. Knowledge of individual filter media is also necessary for meaningful analysis of filter media mix performance. This research focuses on relevant geotechnical engineering properties such as particle-size distribution, compaction characteristics, hydraulic conductivity, water-holding capacity and strength. The following sections describe the sample collection and testing protocols for determining these properties.

3.2.1 Sample Collection and Processing

Compost was purchased from the Western Lake Superior Sanitary District (WLSSD) yard waste management site located on Courtland Street at 27th Avenue West and the waterfront in Duluth, MN (Figure 5). WLSSD compost originated from grass clippings, leaves, garden debris, brush, fresh-cut holiday trees and small quantities of sod and soil (WLSSD, 2015). The samples collected were from piles that had fully completed the composting process and were considered mature.

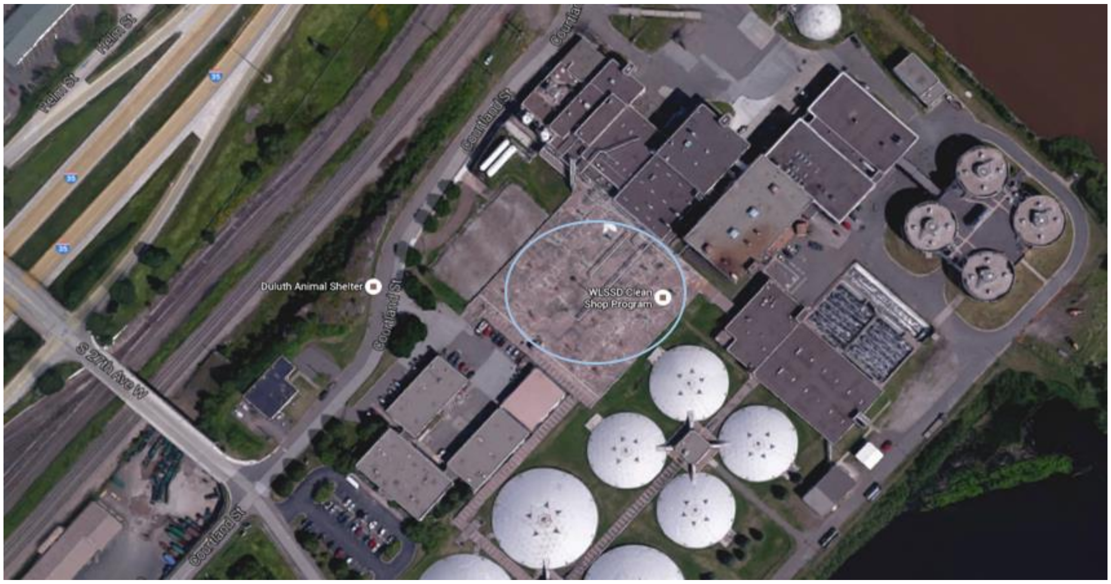

Figure 5. Overhead view of the WLSSD compost site in Duluth, MN.

Figure 6. Compost pile from which samples were taken.

Peat and muck samples were collected from a MnDOT owned gravel pit near Cook, MN (Figure 7). The peat and muck were deposited there in January-February, 2013 after being excavated from a Highway 53 road reconstruction project south of Cook, MN. Peat soil was observed to have dense vegetation while muck areas were sparsely vegetated as pictured in Figure 8.

Figure 7. Overhead view of the gravel pit from which peat and muck were sampled near Cook, MN.

Figure 8. Peat and muck sample area showing densely vegetated peat and sparsely vegetated muck.

Taconite tailings are an iron ore processing by-product with a uniform grain size distribution. Taconite tailings samples originated from the ArcelorMittal Minorca mine near Gilbert, MN (Figure 9) on Nov. 5, 2015. Samples collected for testing were taken from offsite stockpiles (Figure 10).

Figure 9. Overhead view of the ArcelorMittal Minorca mine near Gilbert, MN.

Figure 10. Taconite tailing stockpile.

Screened sand was purchased from Arrowhead Concrete Works Inc. Arrowhead Concrete Works is a distributor of sand sourced from MnDOT Pit number 69511 located near Solway Township, Minnesota. Prior to conducting laboratory tests, muck and peat samples were homogenized using a soil mixing machine shown in (Figure 11) to ensure that samples were representative of the soil mass and to reduce variability.

Figure 11. Top view of soil mixing machine used for homogenizing materials with muck being extruded.

3.2.2 Classification

Soil classification was conducted to aid in the reproducibility of laboratory test results. Taconite tailings, sand, muck and soil from the field test plot site were classified by the Unified Soil Classification System (ASTM D2487-11). For the proper classification of muck and field plot samples, ASTM D2487-11 requires the determination of the Atterberg limits by ASTM D4318. Commercial compost from a MnDOT certified distributor was tested by the U.S. Composting Council (Laboratory Number: 5050829-1/1) to ensure that properties comply with a MnDOT Grade 2 compost classification. Peat was further categorized by ASTM D4427-13. ASTM D4427 required the completion of several additional tests as summarized in Table 11.

Table 11. Summary of tests required for classification of peat (ASTM, 2013).

Parameter	Standard
Fiber Content	ASTM D1997 – 13
Ash Content, pH	ASTM D2974 – 14
Absorbency	ASTM D2980 - 04

3.2.3 Particle Size Distribution

The particle-size distribution of sand, taconite tailings and soil collected from the field test site were determined in accordance with ASTM C136-06. The grain-size distribution of muck was determined by wet-sieving in accordance with ASTM C117-13. Determination of particle-size distribution was conducted for three reasons. First, to classify the media, improving study result reproducibility. The correct identification of media during material collection will improve the performance prediction of a constructed biofilter device. Second, grain-size distribution is used to classify the aggregate fraction of currently specified biofilter mixtures (MnDOT, 2016) and was, therefore, used as a comparison for the selected alternative aggregate, taconite tailings. Finally, the grain-size distribution is a key parameter in many predictive equations for hydraulic conductivity, which were assessed for accuracy in biofilter media mixtures.

3.2.4 Compaction Characteristics

Laboratory compaction characteristics were determined by standard Proctor test in accordance with ASTM D698-12. Determination of the maximum dry density and optimum water content of each material was used to standardize compaction during water-retention and hydraulic conductivity testing. These tests were conducted on soils that were compacted to 85% of maximum dry density.

3.2.5 Moisture Content

Moisture content of study materials were determined in accordance with ASTM D2216 – 10 during water-holding capacity tests. Moisture contents served as comparative measurements of water-holding capacity at both saturation and field capacity. Soil moisture content will also be monitored in field test plots.

3.2.6 Hydraulic Conductivity and Infiltration

The saturated hydraulic conductivity of a soil is approximately equal to its long-term infiltration rate (Figure 12). It follows that the MnDOT Construction Specifications (2016) recommend using field saturated hydraulic conductivity as the design infiltration rate for biofiltration devices. MnDOT (2016) also notes that air entrapment in soils under field conditions makes totally saturated flow unlikely, thereby reducing infiltration rate. Due to this condition, laboratory tests for saturated hydraulic conductivity, which aim to eliminate entrapped air, will likely result in a measured saturated hydraulic conductivity slightly higher than what is expected for *in-situ* conditions. Laboratory saturated hydraulic conductivity testing considered field conditions and aimed to match them as closely as possible.

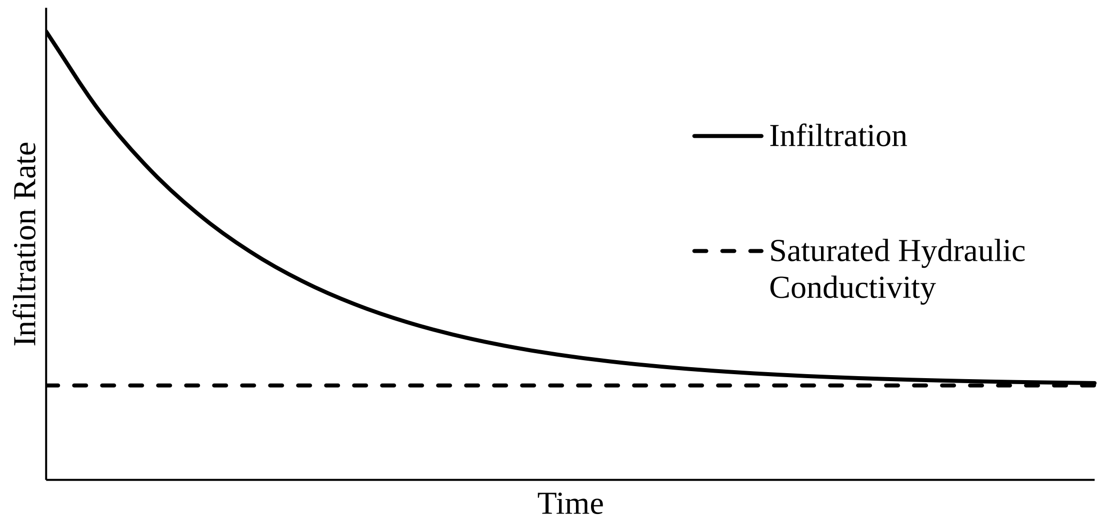

Figure 12. Relationship between infiltration rate and saturated hydraulic conductivity (adapted from Jarrett, 2014).

For the purposes of preliminary mixed media design and comparative analysis, saturated hydraulic conductivity was used as a proxy for *in-situ* infiltration rates. This allowed for the use of established laboratory procedures and reproducible results. To determine the saturated hydraulic conductivity, falling or constant head tests were performed based on the soil particle size. Falling head permeameter (Figure 13. Falling head permeameter equipment setup.Figure 13) testing procedures outlined by Germaine and Germaine (2009) were used for compost, peat and muck. Constant head tests (Figure 14) were performed in accordance with ASTM D2434.

Figure 13. Falling head permeameter equipment setup.


Figure 14. Constant head permeameter setup.

3.2.7 Water-Holding Capacity

Water-holding capacity of the study materials was examined at saturation and at field capacity. Field capacity was defined by applying 33 kPa air pressure until steady-state outflow was reached, using a flow-through pressure cell apparatus (Figure 15) (University of Connecticut Department of Civil and Environmental Engineering, 2011). Permeameter cells containing soil compacted to 85% relative density were deemed saturated when steady-state flow was reached during hydraulic conductivity tests. Once soil was saturated, the moisture content was calculated by mass. Next air at a pressure of 33kPa was applied to the cell until steady-state outflow was reached at which point moisture content was determined in accordance with ASTM D2216-10.

Figure 15. Pressure flow-through apparatus.

3.2.8 Strength Testing

Soil strength testing was performed to provide comparative insight on the strength and stability of study materials. Direct shear tests were performed on sand and taconite tailings to determine the shear strength of each media. Direct shear testing was conducted using an automated direct shear machine (Figure 16) in general accordance with ASTM D3080-04 to determine the effective internal friction angle and effective cohesion.

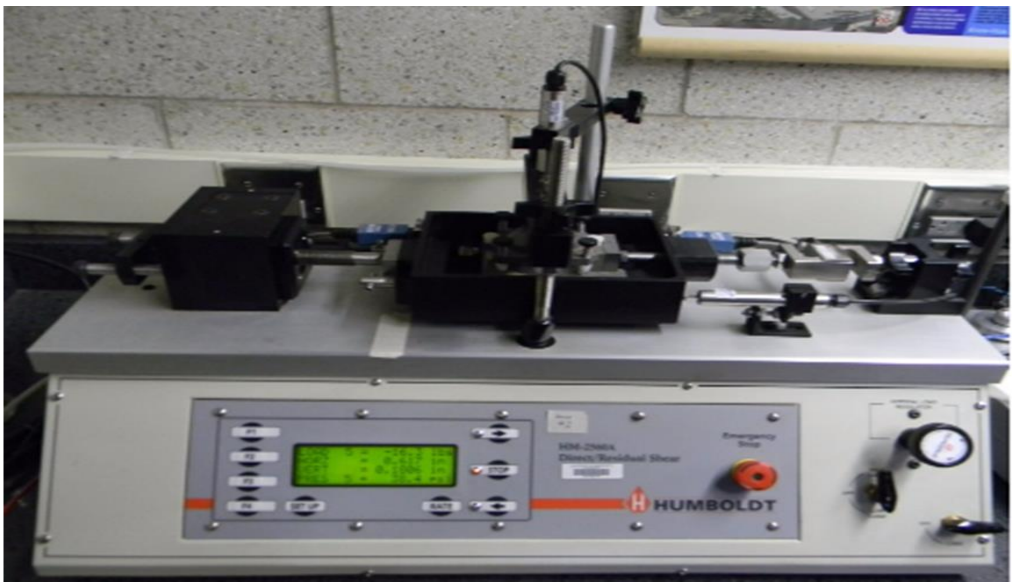

Figure 16. Direct shear machine used for direct shear testing.

3.3 Laboratory Mixed Media Testing

Laboratory mixed media testing focused on determining hydraulic conductivity, infiltration capacity and stability of filter media mixtures. Media mixtures were blended by volume, in accordance with MnDOT (2016), to contain equal portions of peat, compost or muck and sand, taconite tailings or native soil. The new media mixtures were compared to the currently specified combination of sand and compost in a 1:1 mixture. Hydraulic conductivity was determined by falling head permeameter as described in previous sections. Additionally, laboratory infiltration experiments were conducted to determine the infiltration rate and capacity of initially dry media. These experiments were conducted to demonstrate unsaturated hydraulic conductivity rates and to study how observed hydrophobia of dry peat effects infiltration and water absorption.

3.3.1 Predictive Equations for Mixed Media Hydraulic Conductivity

The predictive power of the Hazen (1893) (Equation 1), Kozeny-Carmen (Kozeny, 1927; Carman 1956) (Equation 2) and the Moulton (1980) empirical equation (Equation 3) for predicting hydraulic conductivity of several biofilter mixtures was analyzed to assist future mix designs.

Equation 1. Hazen (1893) equation for predicting hydraulic conductivity.

$$k=C_1D_{10}^2$$

Where k is expressed in centimeters per second and D_{10} (mm) is the grain size at which 10% of the material is finer. C_1, the experimental coefficient was assumed to be 1.0 as recommended by Germaine and Germaine (2009).

Equation 2. Kozeny-Carmen equation for predicting hydraulic conductivity.

$$k=\frac{\gamma}{\mu}\left(\frac{1}{T^2S_0^2}\right)\left(\frac{e^3}{1+e}\right)$$

Where k is again expressed in centimeters per second, γ is the unit weight of water, μ is the viscosity of water, T is a factor selected based on pore shape, S_0 is the specific service area of the soil particles, and e is the void ratio.

Equation 3. Moulton's 1980 equation for predicting hydraulic conductivity.

$$k=\frac{6.214*10^{5}(D_{10})^{1.478}(n)^{6.654}}{(P_{200})^{0.0597}}$$

Where k is expressed in feet per day, D_{10} is the grain-size at which 10% of a sample is passing, n is porosity and P_{200} is the percent passing the #200 sieve.

3.4 Field Pilot Test

Mixed media field testing was developed to focus on determining infiltration capacity, pollutant removal, and vegetative support capabilities of the selected filter media mixtures. A test area, pictured in Figure 17, was selected at the NRRI in Hermantown, Minnesota in coordination with the project technical liaison. Bioslope test plots were constructed on a 1:5 slope (22% grade) in silty or clayey sand.

Figure 17. Field testing pilot plots.

Media mixtures were blended by volume in accordance with MnDOT (2016) to compare 1:1 mixture of native soil and compost to a 1:1 mixture of native soil and peat. Once media was mixed in proper ratios, six three-foot-square media beds (three containing compost and three containing peat) were prepared by placing six inches of treatment media over four inches of gravel to promote drainage via underdrain (Figure 18) to collection vessels which will allow for determination of water quality effects. Beds were then seeded and will be monitored to evaluate vegetative growth by project affiliates. Native soil samples were collected at the time of construction for laboratory characterization. In addition, instrumentation described in the following section, monitoring rainfall, soil moisture content, temperature and overland runoff, will be installed in the spring of 2017 for long term field monitoring.

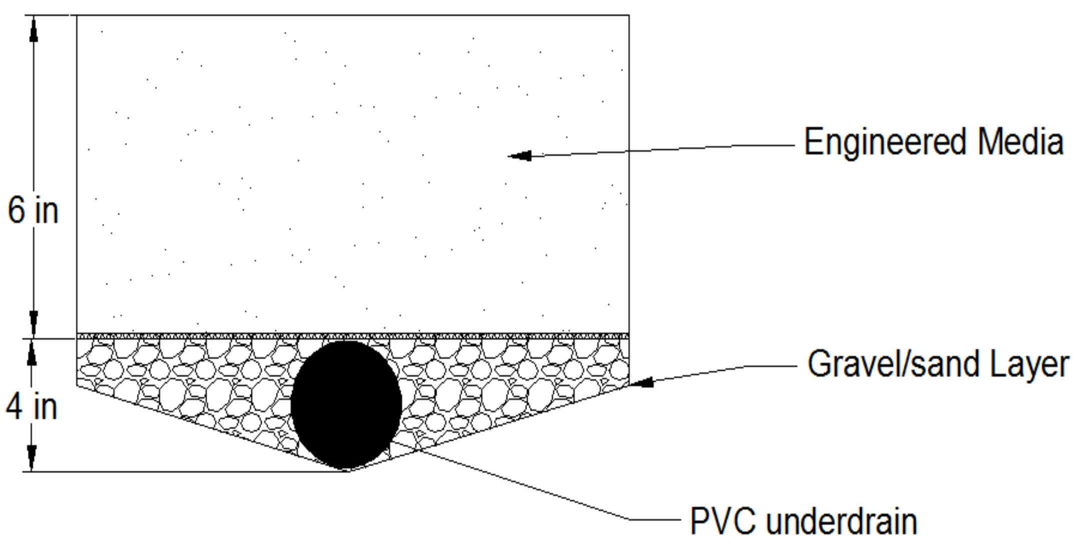

Figure 18. Cross section of mixed media pilot plot.

3.5 Field Monitoring Instrumentation

Field monitoring instrumentation was configured and installed to monitor rainfall, soil-moisture content, temperature and runoff volume. The objective of the monitoring equipment was to compare the performance of compost and peat when added as a soil amendment to native soils. Temperature and soil moisture data loggers were included to acquire knowledge on conditions during which surface runoff was observed, for example, when soil is saturated due to a rapid succession of rainfall events or frozen. Frozen ground conditions are encountered during spring and fall when rainfall and below zero temperatures are likely to be concurrent.

The instruments used include a data logger (Figure 19) with 10 ports to accommodate soil moisture sensors (Figure 20), a rain gauge (Figure 21) and a temperature sensor (Figure 22). A solar panel (Figure 23) was installed to provide a trickle charge for the 10 Amp hour battery to extend battery life. Additionally, to monitor water levels in the surface runoff collection system, pressure transducers were installed (Figure 24). Pressure transducers require an infrared (IR) to USB coupler (Figure 25) to load data from the logger to a computer. A configuration of these instruments is shown in Figure 26.

Figure 19. Multi-channel data logger for data storage.

Figure 20. Soil moisture sensor.

Figure 21. Tipping bucket, automated rain gauge.

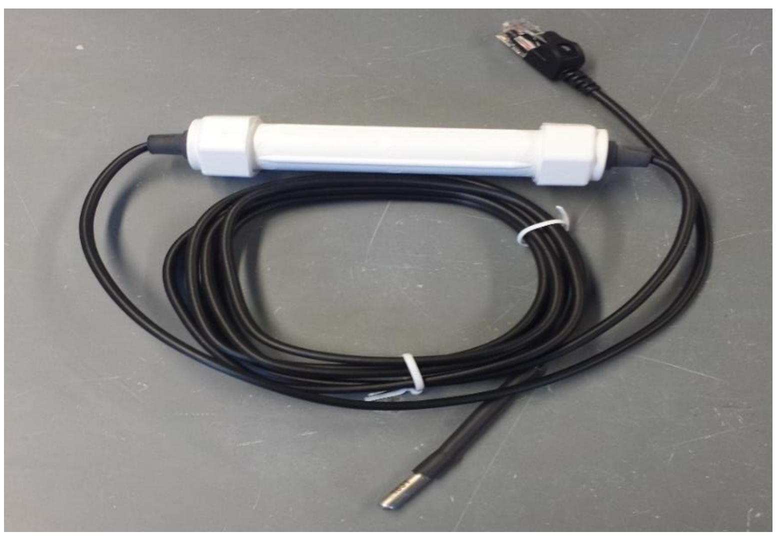

Figure 22. Temperature sensor.

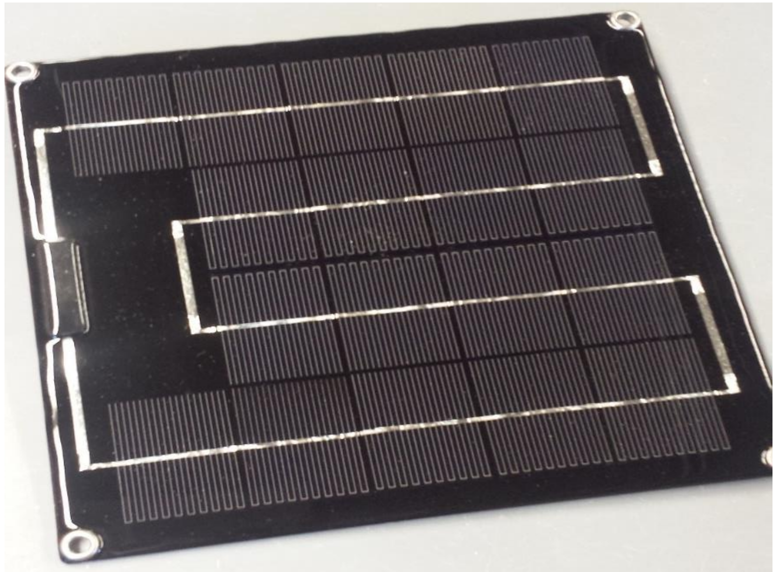

Figure 23. Solar panel for providing trickle charge to data logger battery.

Figure 24. Pressure transducer for continuously measuring water level and temperature.

Figure 25. Optical infrared (IR) coupler for data read-out from HOBO data loggers.

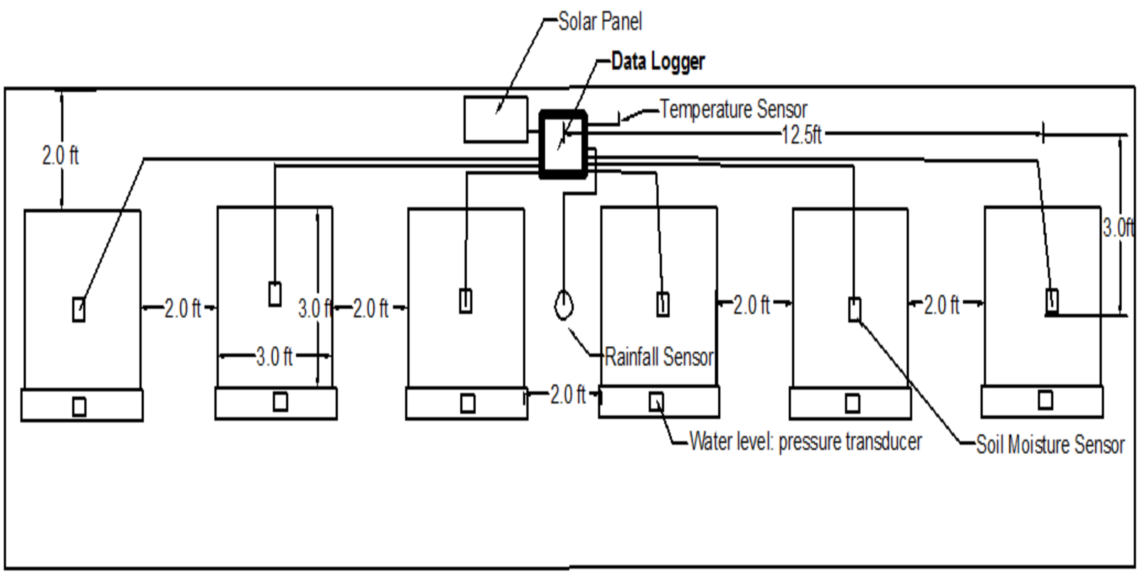

Figure 26. Configuration of bioslope monitoring equipment.

3.6 Conclusion

Chapter 3 outlines laboratory methods that we used to classify, characterize and evaluate stormwater biofiltration media. Additionally, it describes the construction and monitoring instrumentation of field test pilot plots. Methods were selected to be reproducible and to be applicable to various media. Selected laboratory tests focused on determining the compaction characteristics, water-holding capacity, hydraulic conductivity, infiltration capacity, and strength of the proposed alternative media. Field pilot tests were conducted on a single selected media (peat) based on laboratory test results. Instrumentation designed to collect data for the evaluation of biofilter performance will be installed in test plots during the spring of 2017 for long term monitoring.

Chapter 4: Results

4.0 Introduction

Chapter 4 describes the results from the laboratory testing program outlined in the previous chapter. Laboratory testing focused on classification, hydraulic conductivity, water-holding capacity and compaction characteristics of biofilter media. This chapter covers first the classification and characterization of individual media and then the characterization of media mixtures.

4.1 Classification

Soil classification was conducted to aid in the identification of similar materials for use in the field or reproducibility in future laboratory tests. Taconite tailings, sand, muck and field test plot soil were classified (Table 12) in accordance with ASTM D2487-11 (Unified Soil Classification System). Atterberg limits were determined in accordance with ASTM D4318. Liquid and plastic limits for muck were determined to be 64% and 38%, respectively. Soil from the NRRI field test plots had liquid and plastic limits of 24% and 19%, respectively (Appendix 1).

Table 12. USCS soil classification of the tested biofilter materials.

Material	**USCS Classification**
Taconite Tailings	Well-graded sand (SW)
Sand	Poorly-graded sand (SP)
Muck	Sandy organic clay (OH)
Peat	Peat (Pt)
NRRI Field Plot Soil	Silty or clayey sand (SC-SM)

MnDOT specifications for Grade 2 compost ensure proper identification, eliminating the need for further classification. Commercial compost from a MnDOT certified distributor was tested by the U.S. Composting Council (Laboratory Number: 5050829-1/1). Comparing test results with the MnDOT specifications (Table 13) finds that the compost sampled for this research is compliant with Grade 2 compost specification requirements except for soluble salts which exceeded the limit by 1 millimhos per centimeter.

Table 13. Summary of Grade 2 compost requirements (MnDOT, 2016) and compost sample test results (U.S. Composting Council, 2015).

Requirement	Specification Range	Test Results
Organic matter content	≥ 30 %	51%
Carbon/Nitrogen ratio	6:1 – 20:1	12:1
pH	5.5 – 8.5	6.44
Moisture content	35% – 55%	52% as sampled
Bulk density	700 lb per cu. yd – 1600 lb per cu. yd [415 kg per cu. m – 890 kg per cu. m]	1100 lb per cu. yd.
Inert material*	< 3% at 0.15 in [4 mm]	NA
Soluble salts	≤ 10 mmho per cm	11 mmho per cm
Germination test**	80% – 100%	81.7%
Screened particle size	≤ ¾ in [19 mm]	Max particle size: 0.64 inches [16.3mm]
* Includes plastic bag shreds. **Germination test must list the species of Cress or lettuce seed used.		

Peat was categorized as sapric, high ash, slightly acidic, slightly absorbent peat using ASTM D4427-13. ASTM D4427 required the completion of several additional tests as described in section 3.2.2 Classification. Results from those tests are summarized in Table 14.

Table 14. Summary of tests results for classification of peat (ASTM, 2013).

Parameter	Standard	Results
Fiber Content	ASTM D1997 – 13 Standard Test Method for Laboratory Determination of the Fiber Content of Peat Samples by Dry Mass	32%
Ash Content, Organic Matter, pH	ASTM D2974 – 14 Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils	61%, 54% 6.5
Absorbency	ASTM D2980 - 04(2010) Standard Test Method for Volume Mass, Moisture-Holding Capacity, and Porosity of Saturated Peat Materials	204%

4.2 Particle Size Distribution

Determination of the particle size distributions (Figure 27) of taconite tailings, sand and field test plot soil were conducted in general accordance with ASTM C136-06. The grain-size distribution of muck was determined by wet-sieving in general accordance with ASTM C117-13. The uniformity coefficient (C_u), coefficient of gradation (C_c), percent finer and effective diameter at 10%, 30%, and 60% passing (D_{10}, D_{30}, & D_{60}, respectively) of sand and taconite are presented in Table 16. Particle size distributions were used both for soil classification and for MnDOT specification compliance.

Table 15. Grain-size parameters for sand and taconite tailings.

	D_{10}	D_{30}	D_{60}	C_u	C_c	% finer
Sand	0.18	0.39	0.98	5.60	0.89	1.26
Taconite Tailings	0.17	0.45	1.20	7.06	0.99	3.91

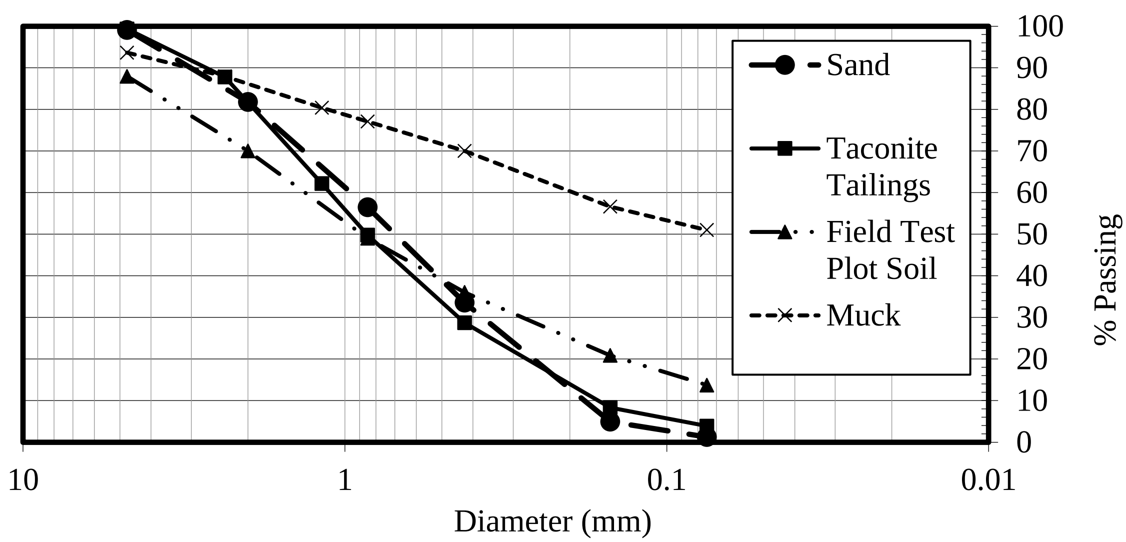

Figure 27. Particle-size distributions for sand, muck and taconite tailings.

4.3 Compaction Characteristics

Results from the standard Proctor test for the determination of maximum dry density and optimum moisture contents (Table 16) reveal the similarity between taconite tailings and sand (Figure 28). The compaction curve for the silty or clayey sand (Figure

28) shows a maximum dry density of 18.2 kN/m^3 and an optimum moisture content of 13%. Peat and compost are also similar with a relatively low maximum dry density (Figure 29). Peat was tested at seven different moisture contents and was found to have a maximum density of 5.7 kN/m^3 at an optimum moisture content of 75%. As the moisture content of peat diverged from 75%, density decreased to between 4.5 and 5 kN/m^3 (Figure 29). Muck was found to have a maximum dry density of 13.4 kN/m^3 and an optimum moisture content of 20% (Figure 30). An evaluation of the native soils at the selected field site was also undertaken.

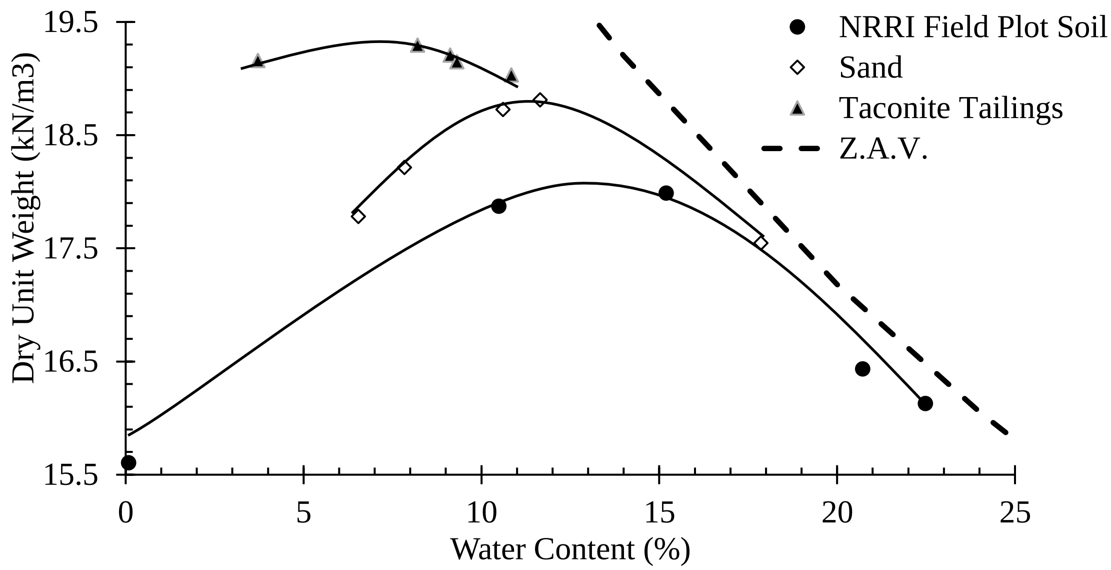

Figure 28. Standard Proctor compaction curves for sand, taconite tailings and field plot soil.

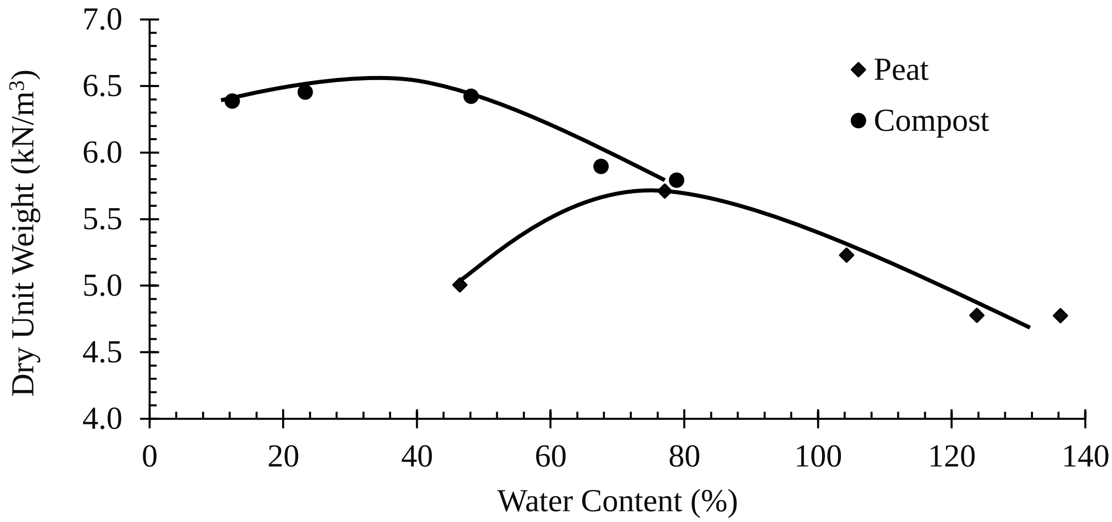

Figure 29. Standard Proctor compaction curves for peat and compost.

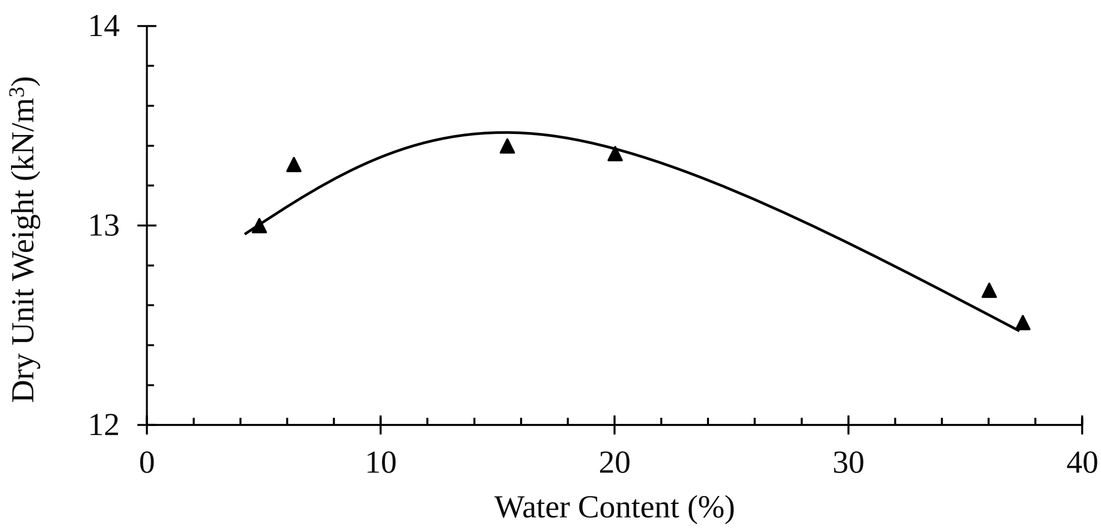

Figure 30. Standard Proctor compaction curves for muck.

Table 16. Maximum dry density and optimum moisture content of individual biofilter media.

Material	**Maximum Dry Density (kN/m^3)**	**Optimum Moisture Content (%)**
Sand	19.1	13%
Taconite Tailings	19.4	8%
Compost	6.5	35%
Peat	5.7	75%
Muck	13.4	20%
NRRI Test Plot soil	18.2	13%

4.4 Hydraulic Conductivity, Infiltration and Water Holding Capacity

The hydraulic conductivity at 85% of maximum dry density was determined by constant head test for taconite tailings and sand. Muck, peat, and compost were tested under at the same density using a falling head test. Results (Table 17) show that taconite tailings have a conductivity slightly lower than sand. The hydraulic conductivity of peat samples had a conductivity higher than that of compost by two orders of magnitude. This is attributed to the fibrous structure of peat which increases the amount and connectivity of pores in the soil structure. Muck was observed to have a relatively low conductivity which is consistent with its high fines content.

Table 17. Average hydraulic conductivity of individual media.

Media	Saturated Hydraulic Conductivity (cm/sec)
Sand	$6.0*10^{-3}$
Taconite Tailings	$2.2*10^{-3}$
Compost	$4.5*10^{-5}$
Peat	$3.9*10^{-3}$
Muck	$7.0*10^{-6}$

Construction specifications (MnDOT, 2016) call for a mixture sand with MnDOT Grade 2 compost. The hydraulic conductivity of these specified materials served as performance criterion. Several additional mixtures of sand with varying peat, compost or muck percentages were tested to demonstrate their effect on hydraulic conductivity (Figure 31). All organic soils decreased hydraulic conductivity, with muck showing a severe decrease in conductivity at relatively low percentages (<15%). Peat and compost mixtures had similar hydraulic conductivities for mixtures between 30%-70% sand. The effect on the hydraulic conductivity of several mixtures also shows a trend of reduced conductivity with increased organic matter regardless of the soil type (Figure 32). This demonstrates that the organic matter percentage of a soil added to a sandy soil exerts some control on hydraulic conductivity independent of its classification. Additionally, the hydraulic conductivity of loose and compacted mixtures containing 50% peat or compost are shown in (Figure 33). Compacted mixtures showed a reduced conductivity demonstrating the importance of specifying density when setting field testing specifications.

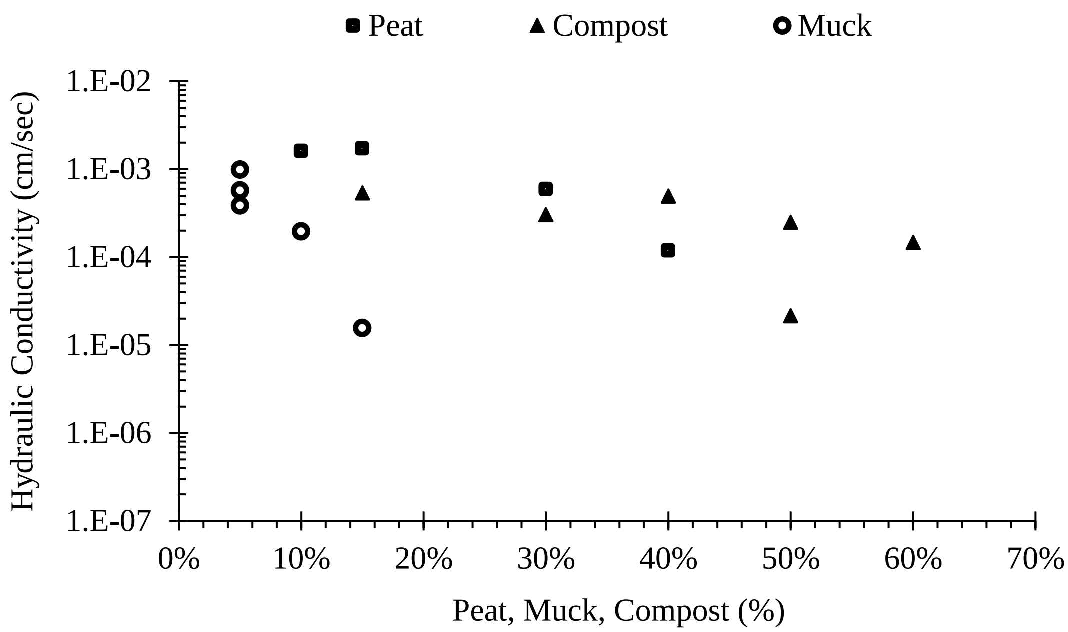

Figure 31. Hydraulic conductivity of concrete sand with increasing percentage of peat, compost or muck.

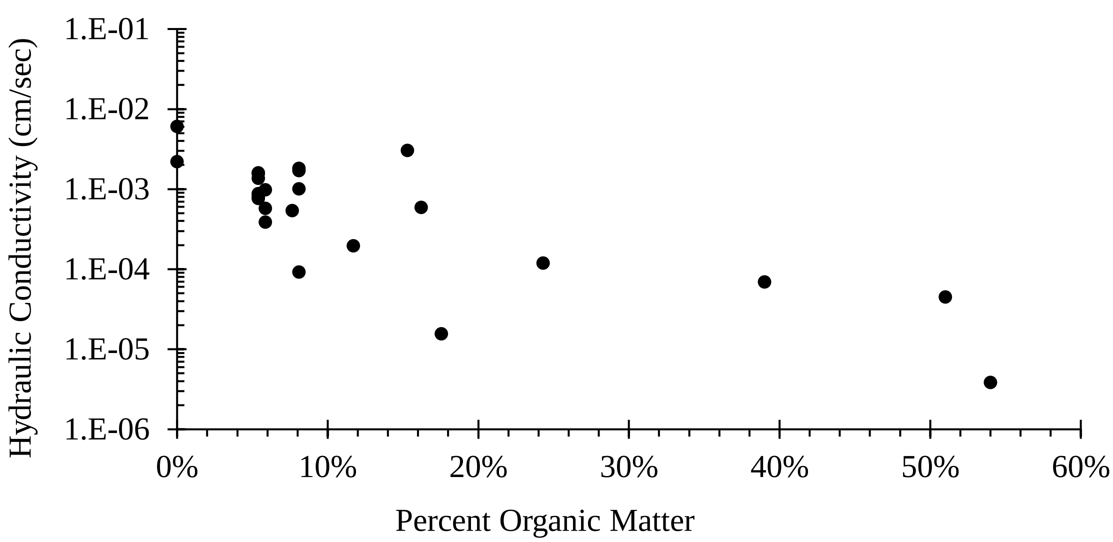

Figure 32. Hydraulic conductivity of mixtures with varying organic matter percentage.

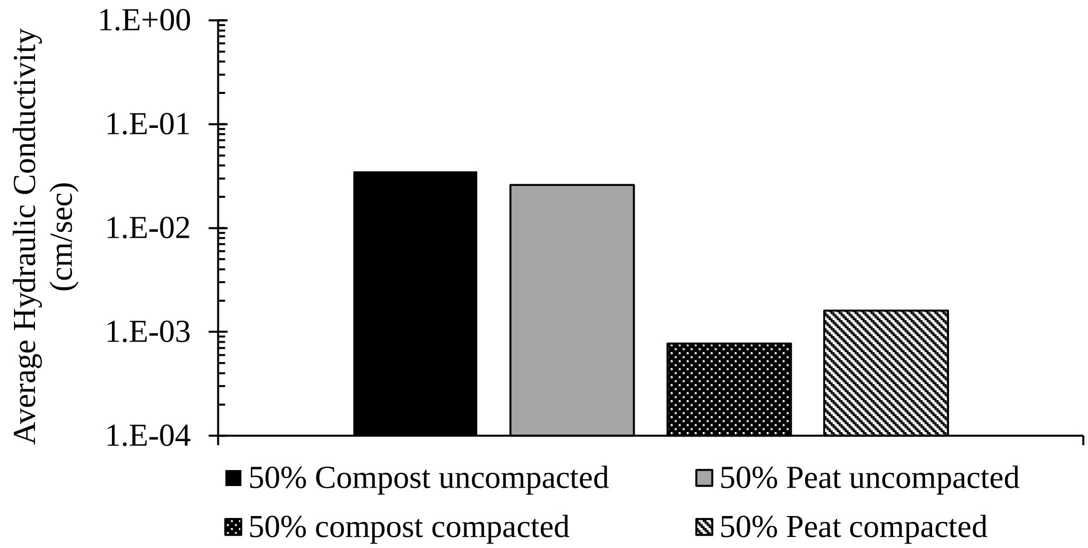

Figure 33. Effect of compaction on mixtures of sand with peat or compost.

A comparison of measured hydraulic conductivities against those predicted by the Hazen (1893), Moulton (1980) and the Kozeny-Carmen (Kozeny, 1927; Carman 1956) equations were conducted to assess the accuracy of these models for biofilter media mixtures (Figure 34). R-squared values for the models when all mixtures were considered were $R^2 = 0.56$, $R^2 = 0.15$, and $R^2 = 0.08$ for the Moulton, Kozeny-Carmen and Hazen equation, respectively. Removing mixtures containing muck improve the performance of the Kozeny-Carmen model to an $R^2=0.43$, but reduced the Moulton's equation R^2 to 0.43. Considering only the typical mixes used in practice, i.e. mixtures containing less than 40% organics improves Hazen's R^2 to 0.10, but does not affect Moulton or Kozeny-Carmen. Hazen is meant to be applied to sandy soil, and is a poor predictor of biofilter media mixture hydraulic conductivity. The poor performance is likely due to the reliance on a single grain-size parameter (D_{10}) and the neglect of void ratio. Since void ratio is decreased by compaction of biofilter mixtures containing high percentages of organic soils, a reduced hydraulic conductivity results. Additionally, the mass based approach of measuring grain-size distribution is complicated by the large range of particle masses in organic, fibrous soils such as peat and compost. The Kozeny-Carmen model slightly under-predicts hydraulic conductivity but performed better than Hazen's equation due to its' consideration of void ratio, specific surface area, and pore shape. The Moulton equation slightly over-predicts hydraulic conductivity, but performed the best overall. Based on these findings it is recommended that the Kozeny- Carmen and Moulton equations be used to estimate a high and low range for biofilter media mixtures' hydraulic conductivity.

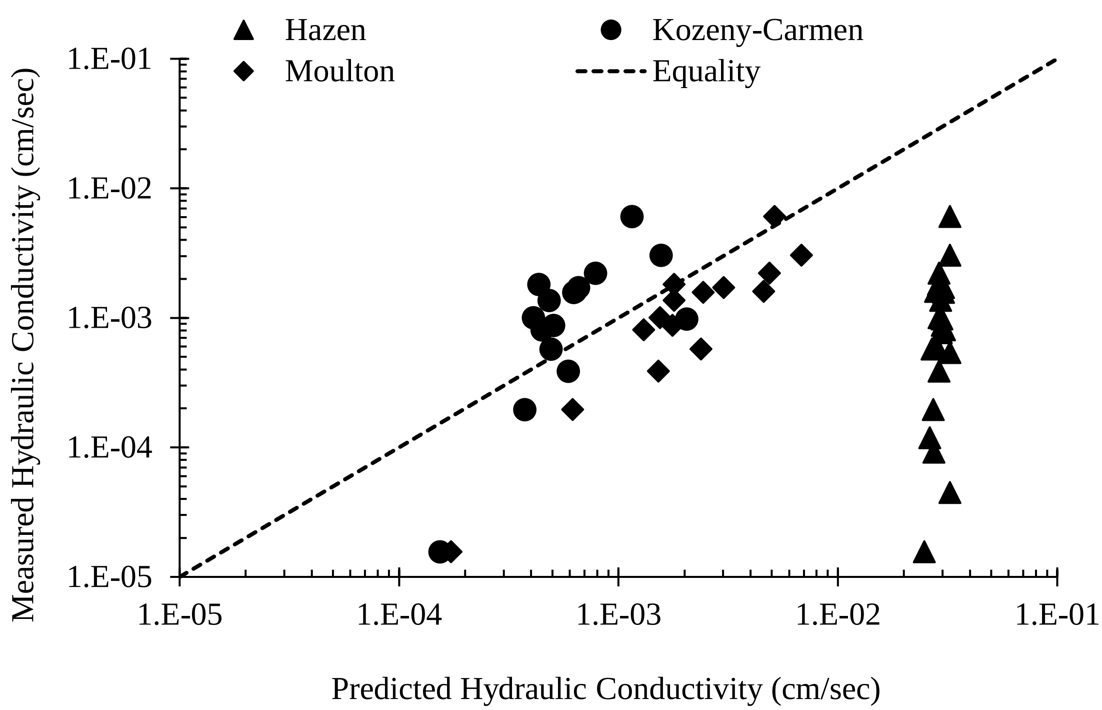

Figure 34. Comparison of predictive models for hydraulic conductivity.

In addition to standard constant and falling head experiments, laboratory infiltration experiments were conducted to determine the infiltration curve into dry media mixtures. These experiments were conducted to demonstrate infiltration rates and to study how the observed hydrophobia of dry peat effects infiltration and water absorption. Results from these experiments (Figure 36) show that peat and compost have similar infiltration rates and infiltration capacities when added to sand in a 50:50 ratio.

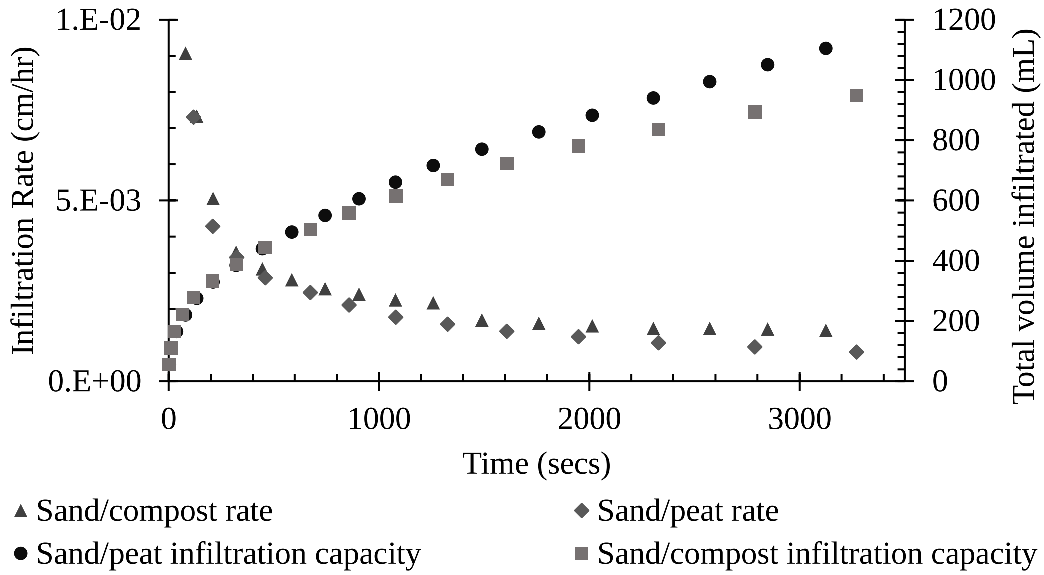

Figure 35. Infiltration rate and capacity of 50:50 mixtures of sand and peat or compost at 85% relative density.

Moisture holding capacity of the study materials (Figure 36) was also examined at saturation and at field capacity using a flow-through pressure apparatus. Cells containing soil compacted to 85% relative density were deemed saturated when steady-state flow was reached during hydraulic conductivity tests. Once saturated, moisture content was determined. Next, air at a pressure of 33kPa was applied to the cell until stead-state outflow was reached at which point moisture content was again determined in accordance with ASTM D2216-10. Results from individual media tests show that peat holds more moisture than muck or compost and that peat and compost have a similar ability to increase the moisture holding capacity of sandy soil.

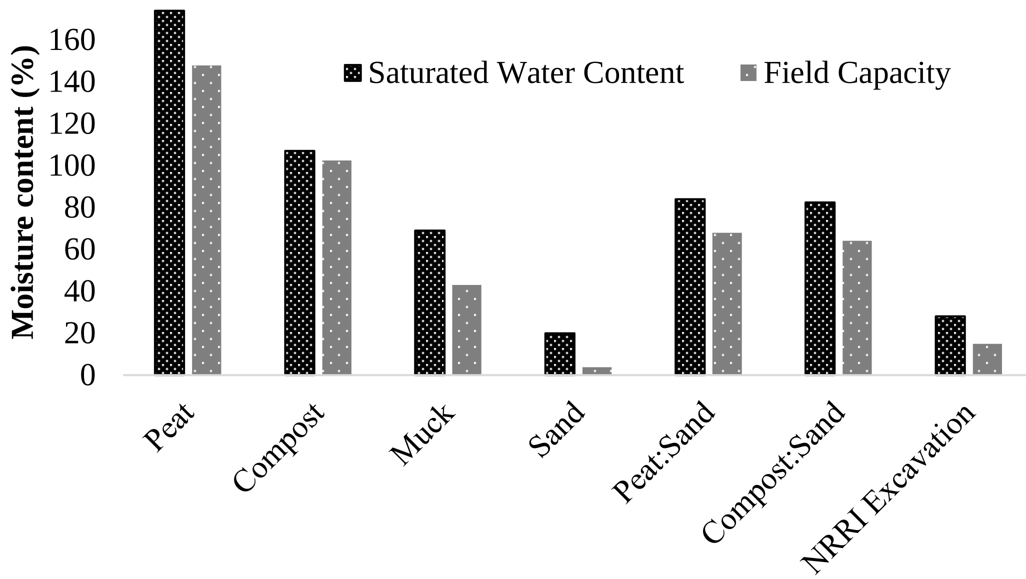

Figure 36. Moisture holding capacity of tested media at saturation and field capacity.

4.5 Strength Testing

Effective internal friction angle and cohesion of sand and taconite tailings were determined by direct shear tests. Figure 37 shows peak shear stress for varying normal stresses applied to sand or taconite tailing samples. The peak effective friction angle for sand was measured at 31° while taconite tailings had a peak effective friction angle of 38°. For related data, see Appendix 1.

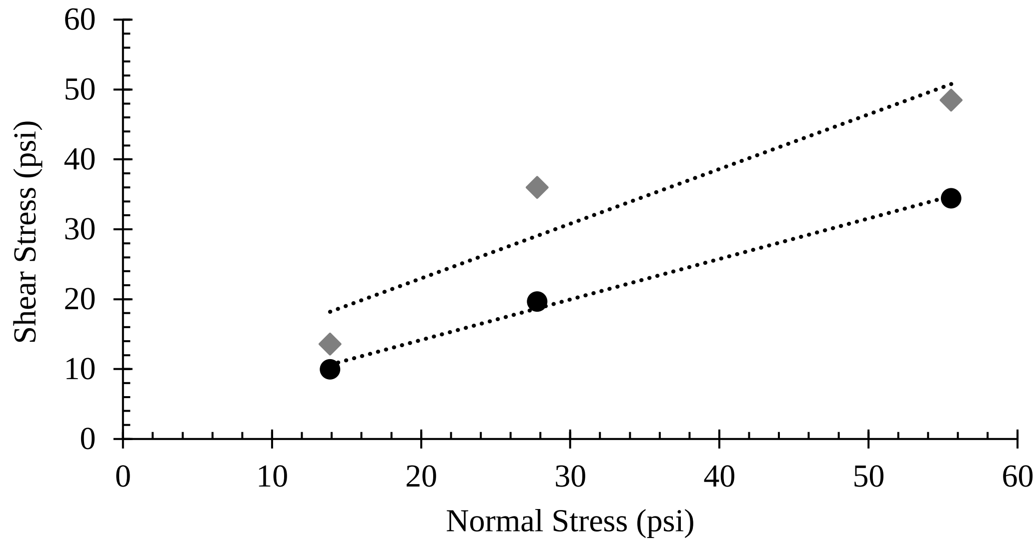

Figure 37. Direct shear test results for sand and taconite tailings.

4.6 Conclusions from Laboratory Testing

Individual media including sand, taconite tailings, compost, peat and muck were tested for grain-size distribution, compaction characteristics, hydraulic conductivity and moisture holding capacity. Sand and taconite tailings were also evaluated for shear strength. Media mixtures were then mixed by volume and tested for hydraulic conductivity, infiltration rate, infiltration capacity and moisture holding capacity for comparison to currently specified mixtures of sand and compost. From these laboratory results, the following conclusions were drawn.

Sand used for this research is poorly-graded (SP) while the taconite tailings are well-graded (SW). Taconite tailings and sand have maximum dry densities of 19.4 kN/m^3 and 19.1 kN/m^3 respectively. The hydraulic conductivity of sand was $6.0*10^{-3}$ cm/sec while taconite tailings had a conductivity of $2.2*10^{-3}$ cm/sec. The friction angle of sand was measured at 31° while taconite tailings had a friction angle of 38°. These results indicate taconite tailings have a higher shear strength than sand which may make them more stable on sloped surfaces. Due to their similar physical properties, the hydraulic and geotechnical performance of these materials is similar, making them a possible alternative from a civil engineering perspective. Non-compliance in grain-size distribution may preclude its recommendation for use in biofilters.

Peat materials performed as well or better than compost in all hydraulic and geotechnical tests. Peat has a high moisture holding capacity, hydraulic conductivity, and performs similarly to compost when added as an amendment to sandy soils. Both materials increase the moisture-holding capacity which will aid in NPDES permit compliance. Peat may also show some resistance to a reduction in hydraulic conductivity when subjected to a compaction effort when compared to compost. While the peat samples used in this research performed well, previous literature reviews have revealed large variability in peats' hydraulic properties depending on origin and degree of decomposition. Due to this variability, it may be prudent to evaluate peat materials on a case-by-case basis when used in stormwater treatment devices. Evaluation should include classification by ASTM D4427-14, determination of water-holding capacity and hydraulic conductivity.

The material described as muck and used in this research classifies by the USCS as sandy organic clay. Muck has deleterious qualities that preclude recommendation for use in biofilter media mixtures including a low hydraulic conductivity and low workability. The high clay content of the studied muck material impedes infiltration which may increase the probability of overland flow when used in bioslopes.

Additionally, muck material was found to be difficult to mix, adheres to equipment, and when dried becomes hard and impermeable.

An analysis of biofilter media mixtures indicated that peat performed as well as compost in hydraulic conductivity and water-holding capacity tests. Based on these mixtures it was also determined that the performance of the Moulton (1980) and Kozeny-Carmen (Kozeny, 1927; Carman 1956) equation are superior to the Hazen (1893) equation for predicting the hydraulic conductivity of biofilter media mixtures. The Kozeny-Carmen equation slightly under-predicts and the Moulton equation slightly over-predicts the hydraulic conductivity of biofilter mixtures. Based on these findings it is recommended that the Kozeny- Carmen and Moulton equations be used together to estimate a possible range for biofilter media mixtures' hydraulic conductivity.

Chapter 5: Conclusions, Recommendations and Future Extensions

5.1 Introduction

Chapter 5 summarizes the findings from laboratory testing, conclusions, recommendations, practical applications and future project extensions. The conclusions and recommendations that follow are based on work conducted in this study as well as concurrent studies by project affiliates who were investigating biological and environmental aspects of the study materials (MnDOT, 2017). Finally, project extensions describe the long-term monitoring of biofilter test plots for soil moisture, rainfall and runoff.

5.2 Conclusions and Recommendations

Currently, soil amendments for stormwater bioslopes and bioswales specify the use of MnDOT grade 2 compost which must be purchased from a certified distributor. While compost satisfies requirements of providing vegetative growth, water quality improvement and a reduction in surface runoff, the beneficial reuse of peat soils salvaged from construction projects offer these benefits at a lower cost. Muck and taconite tailings were eliminated from further consideration as a soil amendment due to several concerns. While muck improves water-holding capacity in sandy soils, it also severely reduces hydraulic conductivity due to its' high fines content. Additionally, project affiliates determined that muck demonstrated a limited ability to enhance plant growth, moderate water quality improvement capabilities and a low degree of constructability. Taconite tailings had similar geotechnical properties to sand, however the high density led to concerns of inhibitory transportation costs. Concerns from the project environmental engineer of pollutant leaching also made taconite tailings a less attractive option (Meijun Cai, personal communication, 2016).

5.3 Practical Application and Concerns

Salvaged peat mixed in sandy soil can improve vegetative growth, effluent water quality and water-holding capacity as well as compost in a laboratory setting. Possible problems with using peat soils in the field include the inherent variability in physical properties of soils classified as peat and the continued decomposition of peat once excavated. Hydraulic conductivity and water-holding capacity are largely controlled by physical properties making the performance of salvage materials difficult to predict. Also, the continued decomposition of peat soils once exposed to oxygen could lead to decreased hydraulic conductivity over time. For these reasons, engineers or designers should determine the classification, water-holding capacity, and hydraulic conductivity of peat soils from different sources prior to use in constructed of bioslopes and bioswales.

5.4 Future Extensions

This project included the design, construction and instrumentation of bioslope field test plots. Instrumentation of the test plots was configured to provide long term monitoring of soil moisture-content, rainfall, runoff and temperature. An extension of this project will focus on collecting field data and determining compliance with NPDES permit requirements.

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Appendix 1

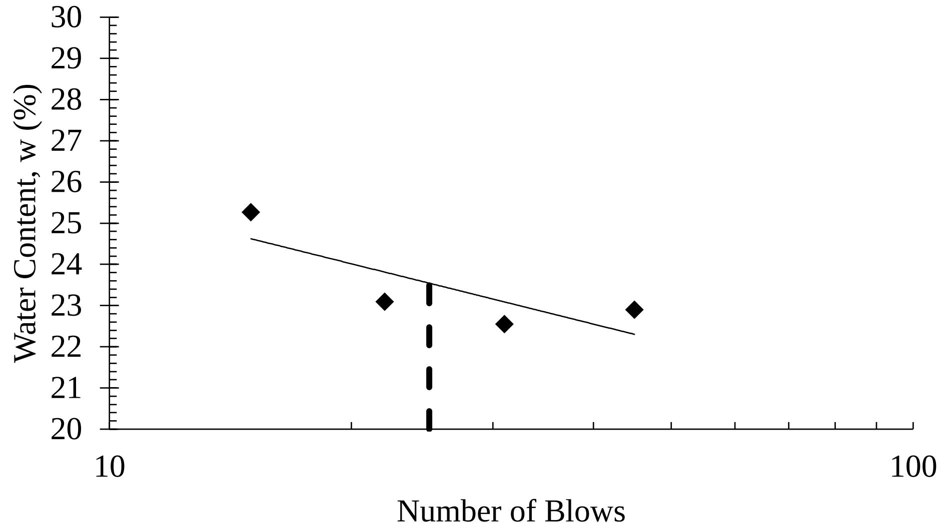

Figure 38. Atterberg limits test results for NRRI filed test plot soil.

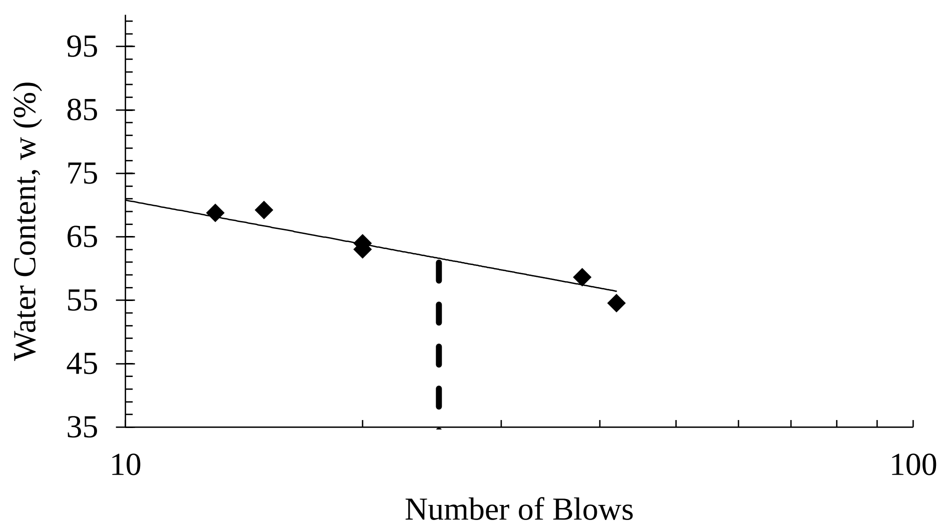

Figure 39. Atterberg limits test results for muck.

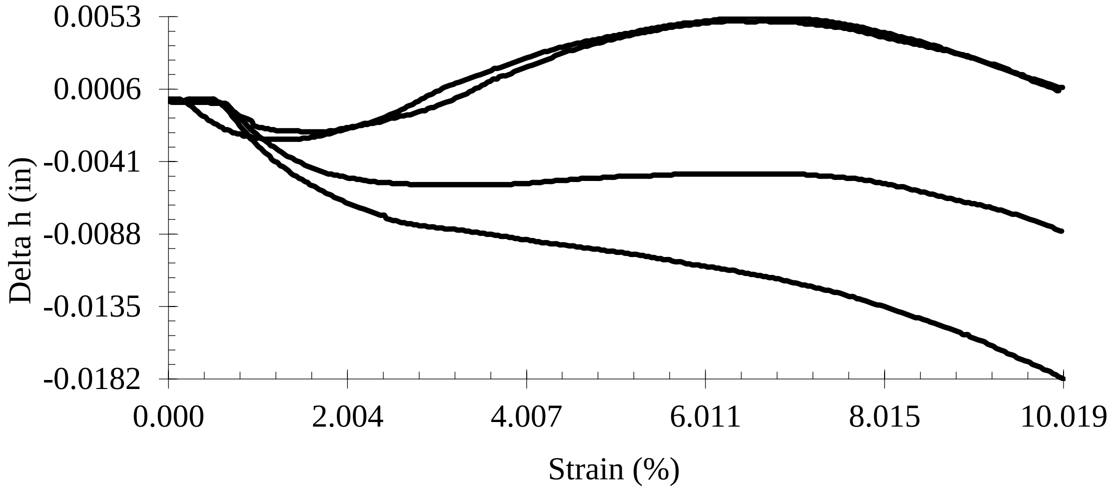

Figure 40. Vertical deformation versus strain from direct shear test of sand.

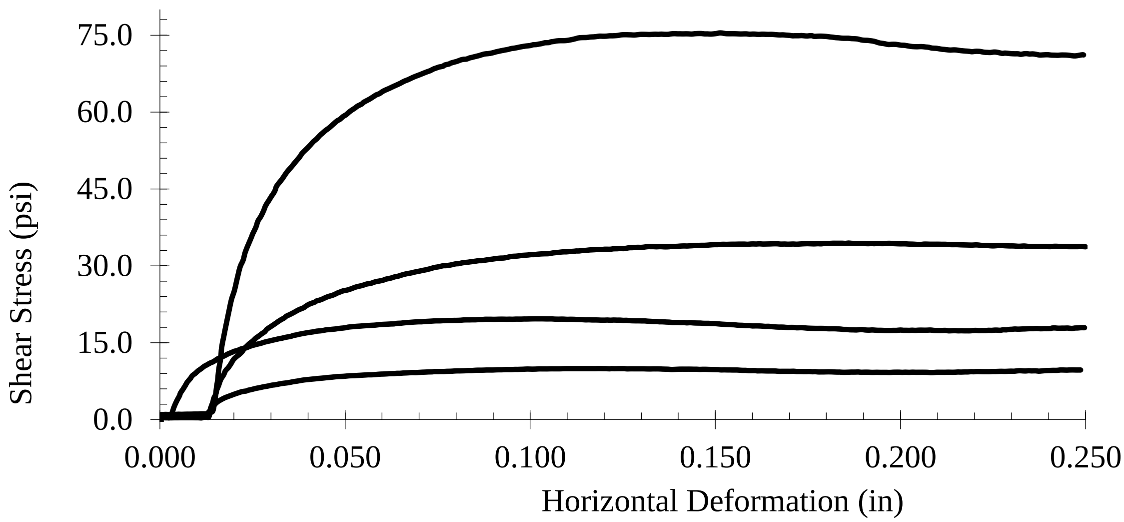

Figure 41. Shear stress versus horizontal deformation from direct shear test on sand.

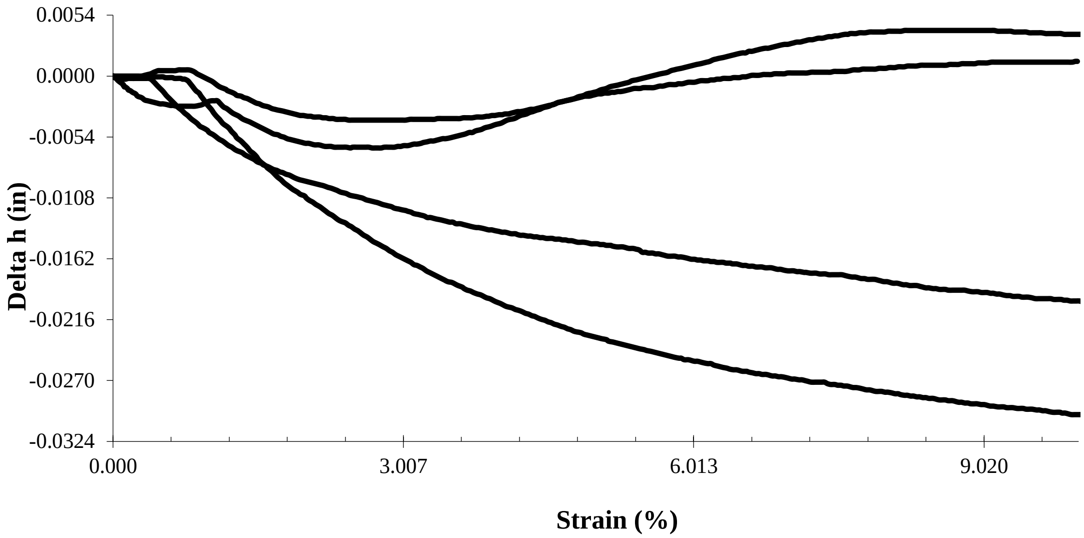

Figure 42. Vertical deformation versus strain from direct shear test of taconite tailings.

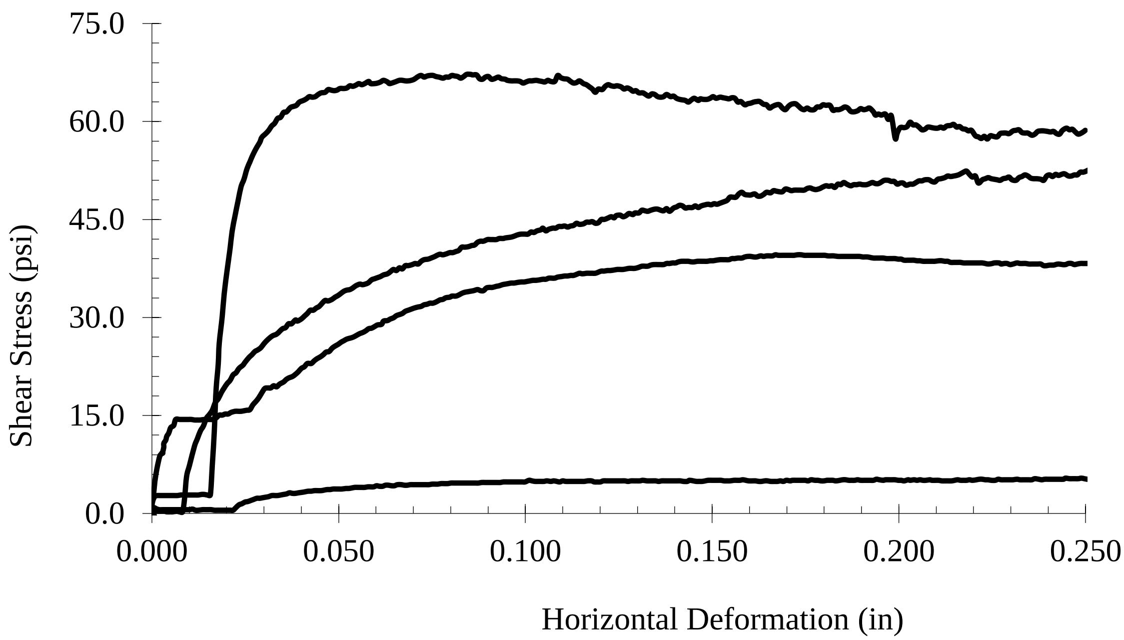

Figure 43. Shear stress versus horizontal deformation from direct shear test on taconite tailings.